



Wireless Network Architecture for Future Smart Grid Machine to Machine Communications

A thesis submitted in fulfilment of the requirements for the degree of
Doctor of Philosophy

Nazmus Shaker Nafi

B.Eng. (Communication), International Islamic University, Malaysia
M.Phil. (Computer Engineering), University of Newcastle, Australia

School of Engineering

College of Science, Engineering and Health

RMIT University

August 2017

Declaration

I certify that except where due acknowledgement has been made, the work is that of the author alone; the work has not been submitted previously, in whole or in part, to qualify for any other academic award; the content of the thesis is the result of work which has been carried out since the official commencement date of the approved research program; any editorial work, paid or unpaid, carried out by a third party is acknowledged; and, ethics procedures and guidelines have been followed.

I acknowledge the support I have received for my research through the provision of an Australian Government Research Training Program Scholarship.

Nazmus Shaker Nafi
30/08/2017

To my parents
Md. Nazrul Islam and Nasrin Islam

Acknowledgement

I would like to express my deepest gratitude to my principal supervisor Associate Professor Mark A. Gregory for his invaluable support and dedication throughout this journey. He was very supportive, enthusiastic and energetic; and extended help whenever needed. I also thank my associate supervisor Dr. Manoj Datta for his timely advice and motivation. He was always there as a true well-wisher and inspired me with enlightening discussion. Special gratitude and thanks goes to my mentor Dr. Khandakar Ahmed who provided valuable ideas and advice throughout the doctoral studies. His thoughtful and sincere comments have helped me prepare this dissertation.

I would like to acknowledge the tremendous sacrifice made by my parents. Without their love, firm determination and motivation it would have been impossible to come this far. In this arduous journey, my wife, Nasheen was always beside me with immense patience and loving support. Last, but not least, I would like to thank my younger sister, Noboni, for her support and encouragement.

Abstract

Transformation of the conventional power grid into an efficient power delivery network is an important advance that will benefit consumers, business and the environment by providing improved integration of renewable energy, including solar and wind. A reliable, low latency communication system is a fundamental requirement for smart power grids. To achieve bidirectional energy distribution capability and to support diverse Smart Grid (SG) applications, the modern SG requires the capacity to handle the traffic generated by machine to machine (M2M) communication infrastructure. Successful integration of numerous SG applications, renewable energy sources and Electric Vehicles (EVs) into a conventional power grid would not be possible without a communication network that has been designed to support the needs of the new and innovative renewable power generation, distribution and storage technologies. While the legacy communication infrastructure, utilized to support the existing power network, fails to support all of the SG functionalities, Software Defined Networking (SDN), based on wireless communication systems, has the potential to provide an effective solution. SDN offers a range of features that fulfill the unique requirements of the SG applications. Being a new networking paradigm, SDN remains to be implemented for SG M2M communication scenarios and there remain a number of challenges that need to be overcome.

M2M communication protocols and standards provide a starting point for the broader development of SG communication networks that can be enhanced by abstracting high-level network functionalities. The aim of this research was to carry out an in-depth study on the future SG communication networks and to propose solutions to identified limitations of existing communication networks. Keeping this intention in mind, the study first focuses on the SG application modeling techniques based on the traffic requirements and power supply load profiles. To address the dynamicity of the traffic model and demand load curve, a series of analytical models and smart algorithms were developed. SG application models were developed and evaluated using a range of scenarios reflecting typical usage. Heterogenous network architectures and efficient traffic models were developed to identify an

appropriate wireless communication technology and to maximize the network performance for major SG applications. However, a careful observation of the communication networks ability to manage and control the diverse M2M communications reveals that the inadequate dynamic communication network configuration capability would be a problem for future SG applications.

M2M communication protocols and standards provide a starting point for the broader development of SG communication networks that can be enhanced by abstracting high-level network functionalities. To realize the full potential of the SGs and deployment scenarios it is essential to analyze the major applications and key requirements to develop those applications. Also, it might be necessary to select an appropriate communication technology for each of the power system domains. The study first focuses on the SG application modeling techniques based on the traffic requirement and load supply profiles of the power system. To address dynamicity of the traffic model and demand load curve, a series of analytical models and smart algorithms were developed. The developed SG application models were further evaluated using simulation scenarios and a test bed model. The challenge of selecting an appropriate wireless communication technology and maximizing network performance for major SG applications was handled by developing multiple heterogenous network architectures and efficient traffic models. A comprehensive literature review of the state of the art of SG applications and standards was carried out to develop robust network models utilizing diverse communication technologies. The literature survey immensely helped to develop two novel SG application models, Zigbee based Pilot protection scheme for a smart distribution grid and Vehicle to Grid (V2G) smart load management scheme. Application modelling included detail traffic modelling, developing smart algorithms, analytical models, user load profile analysis, simulation models and test bed setups. Furthermore, a novel WiMax Ranging scheme is presented to improve the random-access mechanism for various periodic M2M applications supported by extensive simulation based performance analysis.

Future SGs will be overwhelmed by an excessive number of sensor devices that collect various data related to the power system. In a SG Neighborhood Area Network (NAN), wireless sensor networks (WSNs) will play a key role in the development of major SG applications. The application centric WSNs require complex configurations such as well-defined access techniques, transmission and security protocols. Challenges also include development of appropriate routing protocols to tackle resource limitations and delay caused by decentralized WSNs and ad hoc based packet forwarding techniques. A careful observation of manageability and controllability of the diverse M2M network reveals that the inadequate dynamic network configuration capability of the existing SG communication network would be a key bottleneck for future SG. Thus, a novel WSN based communication framework is presented exploiting the emerging SDN networking paradigm. SDN would be beneficial for SGs in many ways. By decoupling the control plane and data forwarding plane, SDN facilitates real-time control and integration of network services and applications that can reach down into the network through the controller hierarchy. A higher degree of control over the overall SG communication network would be achievable via the dynamic programmability provided by SDN. The SDN based WSN network must be robust enough to support the adaptive energy dispatching capacity of the modern power system. The proposed communication framework incorporates novel communication features to separate the control plane and data forwarding plane within the SG communication network. This includes detailed modeling of the control and data plane communication parameters to support both delay sensitive and delay tolerant SG applications. The unique SDN features offers a platform to accommodate maximum number of SG applications with highest controllability and manageability. The performance of the SDN based future SG network is evaluated using a simulation scenario that considers realistic user load profiles, wireless standards, the SG premises geographical area and the state of the art of the SG standards.

Although the control plane enables a global view of the data plane and provides a centralized platform to control and deploy new services, physically a single controller in the controller would not be

practical for SG networks. The challenges arise in terms of scalability, security and reliability, particularly in a SG environment. To increase the efficiency of the proposed SDN based WSNs for the SG NAN, the study proposed distributed controllers with a comprehensive analytical model that optimizes the number of distributed controllers to enhance performance of the proposed communication framework in the NAN domain. The proposed framework along with the analytical model derive several solutions, such as the minimum number of controllers to support the switches and M2M devices, accommodate SG applications and a differentiated flow processing technique to support all traffic types within the network. Lastly, the study focuses on developing SDN-based application specific traffic models for the smart distribution grid.

The thesis focuses on three major issues while developing a future SG communication system. Firstly, it identifies major applications and their traffic requirements at different domains of the SG. Appropriate traffic models were developed by designing robust wireless communication network models. Also, application centric smart optimization techniques are adopted to achieve maximum performance and presented with simulation results, statistical analysis and a test bed result analysis. Secondly, to facilitate the centralized controllability and programmability for supporting diverse SG applications within the SG, a novel WSNs communication framework is presented exploiting the next generation SDN paradigm. Both delay sensitive and delay tolerant SG applications were considered based on the traffic requirement to develop the SDN based WSN communication framework in the SG NAN. Smart algorithms were developed at the SDN based WSN application layer to accommodate a large number of SG applications. The framework feasibility is demonstrated by the simulations carried out to verify the model and provide a statistical analysis. Thirdly, the thesis focuses on developing a novel analytical model that can be used to determine the optimal number of distributed controllers and switches in a SG NAN domain. The proposed application centric traffic modelling techniques, SDN based wireless communication framework and analytical models in this thesis can be adapted for research into other communication networks, particularly those that are begin developed for the

Internet of Things and other forms of M2M communications. Also, due to the technology agonistic characteristics of the analytical and traffic models, they can be used in the development of various wireless networks, particularly those that focus on wireless sensor networks, more generally than the broader Internet of Things.

Table of Contents

Acknowledgement	iv
Abstract.....	v
Table of Contents.....	x
Table of Figures.....	xii
Table of Tables	xiv
CHAPTER 1. INTRODUCTION.....	1
1.1. SGs and M2M communication.....	3
1.2. Software Defined Networks for SG.....	5
1.3. Research Motivation	7
1.4. Research question 1 and contribution.....	11
1.5. Research question 2 and contribution.....	14
1.6. Research question 3 and contribution.....	16
1.7. List of publications	17
1.7.1. Conference Paper.....	17
1.7.2. Journal paper	18
1.7.3. Book Chapter	19
1.8. Thesis Structure	19
CHAPTER 2. Literature Review.....	21
2.1. Overview	21
2.2. SG end-to-end architecture	21
2.3. Neighborhood Area Network.....	24
2.4. Field Area Network	25
2.5. Workforce Mobile Network.....	26
2.6. SG standard.....	27
2.7. SG Applications and Communication Requirements.....	31
2.7.1. Advance Metering Infrastructure	31
2.7.2. Demand Response	33
2.7.3. Substation Automation.....	36
2.7.4. Distributed Energy Resources.....	39
2.7.5. Wide Area Measurement.....	41
2.7.6. Distribution grid protection	42
2.8. SDN based SG.....	44
2.8.1. SDN NAN Architecture utilising WSN.....	44
2.8.2. Traffic model.....	55
2.9. Potential SDN based SG application models.....	56
2.9.1. Advanced Metering Infrastructure	56
2.9.2. Substation Automation.....	57
2.9.3. Distributed Energy Resources.....	59
2.9.4. Wide Area Measurement System	60
2.9.5. Plug-in Electric Vehicle Roaming.....	61
2.10. Summary	63
CHAPTER 3. Application based traffic modelling and performance analysis.....	65
3.1. Overview	65
3.2. A Novel Zigbee Based Pilot Protection scheme	66
3.2.1. Demand Based Priority Queuing.....	70
3.2.2. Test Bed Experiments and Analysis	71
3.2.3. HetNet Based V2G	72
3.2.4. Performance analysis of HetNet based V2G load management scheme	81
3.3. Advanced ranging scheme for WiMax	84

3.3.1. The WiMAX Ranging Procedure.....	86
3.3.2. Performance Analysis of Ranging Procedure.....	87
3.3.3. The Proposed Ranging Scheme.....	91
3.3.4. Performance analysis of Proposed WiMax Ranging Scheme	94
3.4. Summary	96
CHAPTER 4. SDN based SG NAN framework.....	98
4.1. Overview	98
4.2. Network Architecture of the SDN based NAN	98
4.3. Framework configuration	99
4.4. Communication Model	101
4.5. SDN based Distribution Grid Architecture	104
4.6. Performance analysis of SDN based SG NAN framework	105
4.7. Summary	115
CHAPTER 5. Optimization of Distributed Controllers and Development of SDN based SG NAN Applications	116
5.1. Overview	116
5.2. Proposed Mathematical model	117
5.3. Performance analysis of AMI applications in the SDN based NAN.....	121
5.4. SDN based Application specific traffic modeling: G2V	125
5.4.1. Proposed G2V load management scheme.....	125
5.4.2. Performance analysis of SDN based G2V.....	131
5.5. Summary	134
CHAPTER 6. Conclusion and Future Work	135
6.1. Contribution Summary.....	136
6.2. Future research direction	138
References	140
APPENDIX A	148
Proof of Lemma 5.1	149
APPENDIX B	150
Linear Prediction Model	151

Table of Figures

Figure 1.1 Conventional power grid hierarchical placement of different domains.....	2
Figure 2.1 SG end to end network architecture	22
Figure 2.2 Logical architecture of a SG wide area communications network	24
Figure 2.3 NAN Network topology.....	26
Figure 2.4 Mapping of the IEEE standards with the SG architecture.....	27
Figure 2.5 Logical representation of SG Automatic Metering Infrastructure.....	33
Figure 2.6 Intra Substation communication network.....	37
Figure 2.7 Network topology of a Wide Area Measurement System	41
Figure 2.8 SDN based network architecture of heterogeneous communication network for SG.....	45
Figure 2.9 SG Neighborhood Area Network	46
Figure 2.10 Conversation between Zigbee coordinator and network device in a non-beacon enabled mode	50
Figure 2.11 CSMA-CA packet transmission process based a Markov chain theory.....	51
Figure 2.12 Logical architecture of SGs using an SDN paradigm	51
Figure 2.13 Conceptual network architecture of SDN based NAN	54
Figure 2.14 Traffic dissemination model	55
Figure 2.15 Integrated Advanced Metering Infrastructure using wireless technology	57
Figure 2.16 Substation Connectivity using SDN Wireline Access Network Interworking.....	59
Figure 2.17 Connectivity of DERs using LTE-A Femtocells	60
Figure 2.18 Wide Area Measurement using LTE-A Connected Wireless Sensor Networks.....	61
Figure 2.19 Roaming of EVs using SDN and LTE-A	63
Figure 3.1 DCB and/or POTT pilot protection scheme.....	66
Figure 3.2 Message Success Rate.....	69
Figure 3.3 Latency of Pilot Messages under different traffic load.....	69
Figure 3.4 Aggregated Latency in Four Different Cases.....	69
Figure 3.5 Latency of Pilot Message after Applying DBPQ	71
Figure 3.6 Aggregated Latency in Four Different Cases (DBPQ)	71
Figure 3.7 Test Bed Experiments	72
Figure 3.8 Modes of connectivity within the proposed V2G system.....	74
Figure 3.9 Message exchange during the aggregation and discharging session	80
Figure 3.10 Power Supply during peak hours with aggregated power from PEVs	83
Figure 3.11 Aggregated power from different aggregation points	83
Figure 3.12 Number of aggregators required to meet the peak demand	83
Figure 3.13 Total communication load in a single day	84
Figure 3.14 Flow diagram of the WiMAX ranging procedure	86
Figure 3.15 Ranging access load vs. access success rate	88
Figure 3.16 Ranging access load vs. mean access delay	89
Figure 3.17 Ranging Access Load vs. Mean No. of Retires.....	89
Figure 3.18 Ranging Access Load vs. Access Throughput	89
Figure 3.19 Access Success Rate for different no. of ranging codes.....	90
Figure 3.20 Access Success Rate for Different Backoff Window Sizes.....	90
Figure 3.21 Illustration of Time based Ranging Code Re-use Algorithm	92
Figure 3.22 Flow Chart for Network Entry using the Proposed Algorithm for periodic applications.....	93
Figure 3.23 Mean access delay of the proposed scheme	93
Figure 3.24 Mean access throughput of the proposed scheme	94
Figure 3.25 Delay profile of the simulation scenario.....	96
Figure 3.26 Mean application response time	96
Figure 4.1 SDN based WSN to support NAN architecture	99
Figure 4.2 Message exchange between network devices and packet format at different stages	102
Figure 4.3 Distribution network architecture	105

Figure 4.4 Distribution of smart meters in the Fitzroy suburb	106
Figure 4.5 Variation of the number of the switch per controller in terms of processing delay	107
Figure 4.6 (a) Delay profile of different applications and total average delay in the Best-case and Worst-case scenario, and flow processing time	109
Figure 4.7 (a) Packet delivery time taken by different applications in the best-case scenario (b) Packet delivery time taken by different applications in the worst-case scenario.....	110
Figure 4.8 (a) Delay profile of different applications in random scenario (b) Packet delivery time taken by different applications in random scenario.....	111
Figure 4.9 Message exchange between the network devices based on reactive and proactive flow types...	113
Figure 4.10 (a) Delay profile of different applications in case of proactive and reactive flows (b) Packet delivery time taken by different applications in case of proactive and reactive flows	114
Figure 5.1 Routing of packets from the switch to controller based on SBD.....	119
Figure 5.2 Hop counts in a virtual grid	120
Figure 5.3 Optimal number of deployed controllers	121
Figure 5.4 Average delay of AMI traffic in SDN based NAN.....	123
Figure 5.5 Success rate of AMI traffic in SDN based NAN.....	124
Figure 5.6 Uplink delay of AMI traffic in SDN based NAN.....	125
Figure 5.7 Conceptual architecture of proposed SDWSN based NAN.....	126
Figure 5.8 Traffic exchange model.....	128
Figure 5.9 Flow chart of PEV charging algorithm.....	128
Figure 5.10 Grid capacity, demand, power supply and PEV load profile.....	132
Figure 5.11 Total number of PEVs during charging session.....	132
Figure 5.12 Total energy allocation for each NAN based on fairness index	133
Figure 5.13 Total communication network load.....	133

Table of Tables

Table 1.1 Conventional Grids vs. SGs.....	4
Table 2.1 Latency and bandwidth requirement for different SG applications	23
Table 2.2 SG standardization in different regions of the world.....	28
Table 2.3 Approved IEEE standards	29
Table 2.4 IEC standards.....	31
Table 2.5 SG Communication specification for substation automation	40
Table 3.1 Simulation Parameters of the pilot protection scheme	67
Table 3.2 Experimental Results.....	72
Table 3.3 V2G simulation parameter	82
Table 3.4 HetNet Simulation parameters	82
Table 3.5 Ranging Simulation Parameters	87
Table 3.6 Simulation Settings for Periodic SG Applications	95
Table 3.7 Simulation Settings for the SG Event	95
Table 4.1 Major SG application within NAN domain	101
Table 4.2 Simulation settings (SDN based Neighborhood Area Network)	107
Table 5.1 Simualtion Parameters of SDN based G2V.....	131

CHAPTER 1. INTRODUCTION

In the era of advanced automation and broadband communications where every aspect of daily life can be positively affected by new applications; our power grids continue to be operated using antiquated technologies and systems. Although the traditional power grid has been an effective solution for more than 50 years, the future is uncertain as the shift from coal and gas to solar and wind occurs. As more efficient and lower cost batteries come onto the market, the opportunity for bi-directional electricity flows will grow and the open loop system, where power flows from the generation plant to the customer, will cease to be the norm. Also, a lack of situational awareness, poor visibility and control over the power grid is making it more vulnerable to disturbances such as blackouts and brownouts [1][2]. However, there are other pressing issues such as the move to incorporate renewable energy and gradually reduce carbon emissions. In the United States of America power generation produces more than 40% of carbon emissions [3]. Similarly, Australia's total carbon emissions are projected to reach 685 Mt and 801 Mt of CO₂ in 2020 and 2030 respectively, where power generation will be producing 30% of the carbon emissions in both cases [4].

Governments around the world are now putting substantial effort into greenhouse gas emission reduction, to slow the adverse effects of climate change. In Australia, more than 3.5 million people are living in premises with rooftop solar panels. The introduction of Electric Vehicles (EV) has been another promising step towards lower carbon emissions, but it will take some time until EV sales eclipse sales of oil dependent vehicles. The Australian Clean Energy Council estimated that the power produced from Australian rooftop solar panels would soon produce up to 3 GW which is equivalent to the electrical energy needed to run Melbourne's train network [5]. According to the Australian Energy Market Commission EV sales will increase by 20 per cent by 2020 and by 45 per cent by 2030. The Commission also found that there will be an additional peak electricity demand of 1900MW [6].

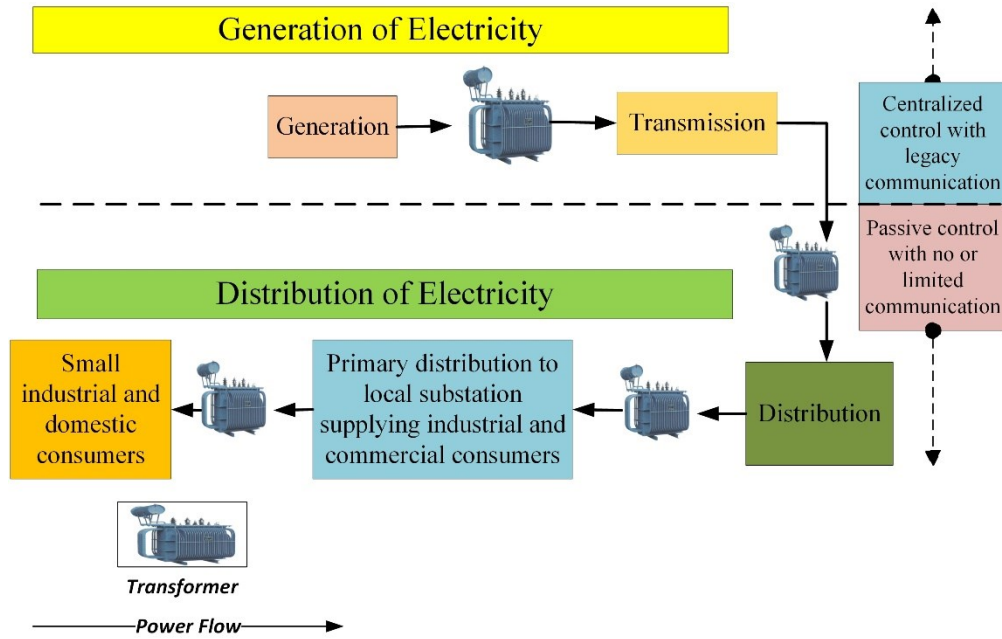


Figure 1.1 Conventional power grid hierarchical placement of different domains

Figure 1.1 shows a traditional power grid where the power flow follows a hierarchical pattern and is functionally unidirectional. The power is generated from the power plant and supplied to the distribution domain via a high voltage electricity transmission network. In the distribution domain, the power is transmitted to customers via substations and a low voltage distribution network. The advent of renewable energy and increasing use of various Distributed Energy Resources (DERs) have made it necessary for the power grid to facilitate bi-directional power flows. To stabilize operational parameters and balance load profiles to enable bi-directional energy flow capability, the existing power grid should be efficiently operated using enhanced control and monitoring technologies. The shift towards bi-directional energy flows and improved control and monitoring of the power grid has led to the evolution of the next generation power grid known as a Smart Grid (SG) and the technologies used to convert the existing power grid into an SG must be reliable, scalable, interoperable, secure and cost effective.

The SG concept has successfully grabbed the attention of the research community and research is now focused on how SGs can be used to address the limitations of the existing power grids. The operation of an SG should be flexible with increased control and monitoring that incorporates smart

communications and remote interaction. For example, SG substations should have the capability to coordinate their local devices autonomously [7].

1.1. SGs and M2M communication

According to the definition provided by the U.S. Department of Energy (DOE), SG is an energy supply network that supports bi-directional power flow, distributed and automated in nature, and permits real-time balancing of demand-supply via distributed and high-speed computing and communication [1]. However, the key differentiator, while converting the existing power grids to next generation SGs, will be designing robust SG compatible communication network infrastructure. Severe drawbacks are associated with the existing power grids [8], such as (1) disjointed architectural configuration; (2) bandwidth limitations for bi-directional communication; (3) interoperability issues between vendor based network components; and (4) inefficient handling of huge data bursts generated from a large number of smart devices. Table 1.1 shows the key characteristics and major differences between conventional power grids and SGs.

According to SG Australia [9] next generation grids will introduce a number of major enhancements to conventional power grids including machine-to-machine (M2M) communications, real-time supply-demand management, asset supervision and improved operational efficiency (e.g. outage management). Research [10] demonstrates various benefits of SGs and Hamilton and Summy [10] projected that in the USA, investment of US\$1 billion in SG technology might generate up to US\$100 billion in Gross Domestic Product (GDP) growth. In the USA, it is predicted that the efficient power consumption behavior possible with an SG will add US\$15–20 billion by 2020. As claimed in [10], SGs could be a key driver of economic development as demand grows for smart buildings and smart transportation systems creating more jobs for a skilled workforce. A study of European SG projects [12] shows that most of the European countries are already at different stages of deploying smart meters. The study also shows that Italy and Sweden have fully installed smart meters while in Finland and Spain first phase deployment will be completed soon. The key reason for the mass roll-out of smart

meters is real-time monitoring and reducing power consumption. The European Electricity Grid Initiative (EEGI) will generate 35% of electricity from the DERs by 2020 in preparation for planned green power production by 2050 [12]. To ensure a robust electricity supply network exists throughout the pan-European region the EEGI is seeking more customer participation and energy efficient schemes such as electric transportation. Generation, transmission and the distribution domain of power grids should have efficient communications and networking infrastructure in order to meet the complex requirements of SGs. Cheng et al. [13] mentioned that via communication infrastructure SGs would be able to gather detailed statistics about power generation, instantaneous or predicted consumption data, storage, and distribution information. According to Cisco SGs are the combination of power grids and the communication networks that collect real-time data on power transmission, distribution and consumption [9]. The two domains of the power grid where SG should impact the most are the transmission and distribution domains, and there is a need for communication protocols designed to support data exchange between different network devices.

Table 1.1 Conventional Grids vs. SGs

	<i>Conventional Grid</i>	<i>SG</i>
<i>Power flow property</i>	Unidirectional	Bidirectional
<i>Generation profile</i>	Centralized	Distributed
<i>Grid configuration</i>	Radial	Network
<i>Integrating DERs</i>	Very rare	Frequently
<i>Sensor Devices</i>	Few	Plenty
<i>Monitoring</i>	Restricted view	Self-monitoring
<i>Control</i>	Limited and passive	Pervasive and active
<i>Outage recovery</i>	Manual restoration	Self-reconfiguration

SG communication requirements vary significantly depending on the SG applications in use. Some of the SG applications are delay sensitive, where signals or other information should be delivered within

a specific period with guaranteed reliability, and SG applications may utilize a low data rate, for example, a device, substation automation system or a Device Response Management (DRM) application. Also, applications may require high bandwidth with flexible delay bounds, such as Advance Metering Infrastructure (AMI), EV Charging and Vehicle to Grid (V2G) power transfer [14][15][16].

1.2. Software Defined Networks for SG

Research into SG communication networks aims to identify an integrated approach that leverages communication technologies and standards while focusing on the management and control of systems found in the existing power grids. M2M communication protocols and standards provide a starting point for the broader development of SG communication networks that can be enhanced by abstracting high-level network functionalities. A one stop communication solution is yet to be developed that facilitates reliable and efficient traffic exchange between the different SG domains and supports the deployment of diverse communication network services and applications. Software Defined Networking (SDN) provides a separation of traffic control and the systems that transfer traffic across the network [17]. SDN is a novel approach to manage and control communication networks that provide a higher level of network functionality abstraction that is appropriate for SG use. SDN provides an efficient, secure, reliable, cheap and flexible topology for SG communications. An SDN based communication architecture for SGs provides the flexibility and low-cost necessary to support the transition from the existing power grids to SGs. Another feature of a potential SDN implementation for SG communications is the optional use of different communication technologies for traffic control and traffic transmission systems. Selection of the appropriate communication technologies will depend on the traffic model developed for each of the SG domains. Multiple applications can be incorporated utilizing SDN that has different traffic patterns, processing priorities, and data expiration times.

The future SG is expected to have high system resilience in order to manage a large number of M2M devices that can introduce greater risk of sudden failure or malicious attack. The pervasive use of new

software in different SG domains endangers the power grid with high vulnerability. The adaptive network configuration capability of the SDN paradigm would be beneficial for SGs as the diverse network can be managed from a single control point. The non-adaptive network configuration of existing M2M networks does not permit run time modification or network device configuration to react to sudden attacks. Also, bandwidth demand would increase exponentially with the rapid increase of diverse SG applications. It would enlarge the horizon of unexpected attacks on the future SG network. On the other hand, in an SDN network, the physical layer switches only forward the packets, allowing flow based traffic dissemination over the network where the flows originate from a central controller. The feature enables real-time dynamic network configuration and could alleviate resilience bottleneck created by existing non-adaptive network configuration.

Wireless Sensor Networks (WSNs) have evolved utilizing ubiquitous wireless communication technologies that provide high-speed, low cost and secure M2M communication [18]. Among the contemporary communication technologies, WSN is particularly suited for use with SG communication networks because of its design for low energy consumption, easy deployment, and Quality of Service (QoS). WSN supports continuous innovation, reduced equipment costs, and open standards that reduce the need for a single vendor solution. For potential SG operators, WSN is an attractive alternative to wireline communication technologies for M2M. A fully integrated SDN based WSN for SG communication networks can offer more than just last-mile connectivity, and WSN based radio networks provide SG operators with:

- state-of-the-art Authentication, Authorization and Accounting (AAA) capabilities for real-time energy metering and implementation of various Demand Response (DR) programs;
- smooth interworking with the existing wired communication infrastructure for substation and feeder automation;
- flexible network topologies that are used to connect DERs and perform a wide range of

distribution management functions;

- remote sensor networks for wide area monitoring applications; and
- real-time data applications for facility coverage, asset tracking, and workforce management applications.

1.3. Research Motivation

In recent times, SDN has become a key focus for communication network research and development. Both academic and industrial experts are deeply motivated by the prospects of the SDN paradigm. The need to gain enhanced network controllability and manageability is the main driving force behind the initiative to convert existing networks to next generation SDN networks. Due to a separation between the data and control planes, SDN offers more manageable network features when compared with conventional networks. Rapid growth in data usage and the emergence of smart technologies has prompted an exponential growth in network device installation of over the past decade. Accommodating a large number of network services and applications is a challenge that is best met with the shift to SDN. Also, proprietary network equipment makes it difficult to implement hardware and software updates in a multi-vendor provisioned network. With SDN, the entire network can be controlled using a single secure monitoring and management platform. Also, SDN facilitates software updates, including network service updates, without directly intervening or physically configuring the network devices. The network can be configured, monitored and controlled using a hierarchy of SDN controllers regardless of vendor specific network devices. In most of the literature, SDN has been designed to utilize the OpenFlow protocol [19]. The OpenFlow framework was proposed by the Open Networking Foundation [20] to develop and test new control mechanisms for large networks. The framework defines a packet forwarding model, flow table generation and update mechanism. The protocol specifically establishes communication between the SDN controller and OpenFlow enabled switches. In an OpenFlow based SDN network, multiple flow tables can be installed or programmed

onto a switch via the controller. Packets arriving at the switch match their header field information with the flow entries stored in the flow table. Packets are forwarded based on the action defined by the flow entry. In the case of a flow miss scenario, the switch sends a flow request to the controller and based on the flow command received from the controller the packets are forwarded to the destination. OpenFlow based SDN is one of the basic solutions derived from the wide horizon of the SDN paradigm.

The power grid today, in most regions of the world, operates using a hierarchical structure where the power flow is unidirectional from generation to consumer premises. The power grid control center has very limited real-time information about the grid components. Thus, it's hard to assess the dynamicity of the power grid environment. Also, due to increased demand for low-cost green power, renewable energy sources are becoming more popular and the power grid increasingly needs to accommodate this growing number of renewable energy sources. The benefit of this wide scale integration of renewable energy resources will only be realized if synchronization and load management through bi-directional power supply can be enabled. Synchronization of DERs and smart load management require advanced monitoring and control systems. The operational grid parameters including current, voltage and frequency should be monitored and stabilized to optimize the demand supply profile.

The modern SG is destined to enable bi-directional power and information flows between the grid equipment. Deploying M2M communication within the SG is performed via separate network domains such as Home Area Networks (HANs), Neighborhood area networks (NANs) and Wide Area Networks (WANs) [21]. In an SG communication network, thousands of M2M devices will be operating in a periodic, semi-periodic or stochastic manner. A massive amount of traffic is expected to be disseminated throughout the network based on the SG application requirement. The diverse traffic patterns need to be handled carefully as there will be multiple applications running with varied delay requirements.

Any changes to power grids are challenging due to complexity and network size, functionality and standard specifications. The modern power grids need to accommodate state of the art SG applications and implement those applications in the most intelligent manner so the power users, government agencies, stakeholders and utility service providers, etc. all are benefited. Furthermore, development and implementation of SG applications possess challenges in selecting the appropriate communication technologies, security issues and grid policies. SG will make the power grid capable of transmitting electrical power in the forward and reverse directions, that is from a power plant to customers and from customers to other customers in the distribution domain [21]. Large scale projects on generating power from renewable sources [22][23] also support the need to transform the power grid into SG. The main reason behind this is to increase the number of power resources to share the generation load of the power plants. Adding more renewable energy sources, with proper synchronization, with the existing generation system may reduce substantial domestic and commercial demand load and reduce costs for both consumers and power system authorities and generators. Smart distribution grid applications [8] such as AMI [24], DR [25], DER [26], V2G [27], etc. carry significant potentials in handling peak shaving, ancillary services, spanning reserves services, etc. With smart modeling of SG applications and successful transformation to SG, the power sector would find a platform to deal with the ever-increasing demand for cheap electrical power.

Transformation towards SG will be highly dependent on the sophisticated communication network and software development. Real-time monitoring and control through large-scale implementation of intelligent devices would require smart traffic engineering and data management. Also, to improve security, efficiency, and reliability of the power network, a robust communication network that enables autonomous system operation is a necessity. In this context, developing a communication network appropriate for SG could be revolutionized by the emergence of SDN paradigm. SDN could be a one-stop solution for managing large scale data flows while running diversified SG applications in the network. According to [28] advanced power grid communication network controllability and

manageability could be achieved by implementing SDN networks along with SGs because of the programmable functionality. By having two distinct layers for controlling and data forwarding tasks an SDN network reduces the burden of configuring a huge number of physical devices installed in the SG [29]. Smart meters and sensors nodes installed in the NAN will increase the need for advanced data layer capabilities. Implementing SDN in a wireless environment with large numbers of wireless sensor nodes or smart meters faces potential challenges. For example, determining the communication framework, defining the network architecture and configuring an optimal number of switches and controllers for the wireless NAN.

The aim of this thesis is to carry out an in-depth study on the overall SG communication framework. Keeping this intention in mind, the study first focuses on the existing wireless solutions proposed in the state of the art literature on the topic and provides a thorough review analysis on the traffic modeling and application characteristic of SGs. Based on the literature gap, two application centric traffic models were developed using WSN and WLAN-WiMax Hetnet. In order to enhance the performance of the WLAN-WiMax HetNet a novel, WiMax ranging scheme is proposed. All the proposed models are presented with simulation results and analysis highlighting the key factors to design the communication network at different SG domains. Careful observation of the network manageability and controllability of the diverse M2M network reveals that the inadequate dynamic network configuration capability of the existing SG communication network would be the key bottleneck for the future SGs. Thus, a novel WSN based communication framework is presented exploiting the emerging SDN networking paradigm. The thesis further develops a comprehensive analytical model that includes optimization of the controller distribution to enhance the performance of the proposed communication framework in the NAN domain. Lastly, an application specific traffic model is presented utilizing the optimized controller distribution in the NAN domain showing the improvement in the overall performance of the SG NAN network.

SDN is destined to overcome the security and privacy issues of the future SG. However, it's important

to note that the main focus of this thesis is to develop an M2M communication framework and applications for the SG environment. The security or privacy issues of the diverse SG network do not fall within the scope of this study. Also, SG has various telecommunication applications like voice over internet (VoIP), Internet, Multimedia, etc. which remain out of the scope of this study.

1.4. Research question 1 and contribution

Research Question 1: What would be the appropriate communication and application models for major SG applications with differentiated traffic pattern and load supply profile.

To answer the Research Question 1, this study investigated available wireless communication standards, such as the IEEE 802.11, IEEE 802.15.4, and IEEE802.16. An extensive survey on WSN, Heterogeneous Network based on WLAN-WiMAX and standalone WiMAX and their usefulness when modeling SG applications at different SG domains have been carried out. The key contributions resulting from Research Question 1 include:

- Identified the major SG applications in different SG domains. An in-depth review of the communication requirements and characteristics was carried out. Based on the analysis, two novel SG applications, such as Pilot protection via protective relays in the smart distribution domain and a V2G scheme have been developed based on WSN and WLAN-WiMAX Heterogeneous networks respectively.
- Identified and analyzed techniques, smart algorithms, parameters and performance matrices need while developing an appropriate analytical model of future SG applications to provide guaranteed QoS.
- Application-centric smart optimization techniques are adopted, and a predictive algorithm was used to maximize the performance of the developed applications. The performance of the enhanced Medium Access Control Mechanisms and traffic dissemination models are presented

along with extensive simulation-based results. The performance of SG applications was found to be particularly dependent on the delay requirements and reliability.

- To accommodate large numbers of M2M devices in SG, a novel WiMAX ranging scheme is proposed that can provide contention-free network access to the periodic M2M applications in an SG such as AMI applications (e.g. Meter data, critical alarm sensors, Phasor Measurement Units, etc.).

From earlier sections, it can be seen that there are specific communication requirements (e.g., data rate, latency, etc.) for SG applications. Communication loads for the majority of the SG applications depend on the load supply profile of the grid. The production, transmission and distribution supply networks consist of hundreds of components, devices, control units and protection devices. With the rise of SGs and renewable based distributed generation, bi-directional power flow in the distribution networks has become inevitable. To maximize reliability and to support time varying bi-directional power flow, it is essential for the components of the electric grids to exchange critical control data with each other and work in a fully meshed manner. With this motivation, the major SG applications of the distribution domain were identified and an application model was developed that considered the communication traffic and load supply profile. To increase the performance of the SG application models and to accommodate large numbers of M2M devices, a smart ranging scheme for WiMAX networks is proposed.

The first application relating to Research Question 1 focuses on a communication model for a smart distribution grid protection scheme. The distribution section of the power grid requires a reliable protection system for the distribution lines and equipment. The protection system should identify faults and ensure appropriate isolation when a fault occurs. Usually, Pilot protection schemes are commonly used for fast fault detection, isolation and restoration (FDIR) purposes in the distribution section of power grids [30]. Additionally, these schemes use high-speed peer-to-peer communication between

the relays at both ends of a distribution line terminal to ensure secure and selective relay tripping. However, the challenge associated with these protection mechanisms is to deliver the fault information within a strict delay boundary through a communication channel that can transmit a binary, on/off, permissive or blocking signal. Therefore, widespread deployment of the Pilot protection schemes to improve communication links is important and will provide fast, reliable and enhanced communications. This study provided:

- A reliable protection scheme in distribution domain.
- A demand based priority queuing technique that enables SG applications to provide reliable and high-speed delivery of the Pilot protection signals
- High-speed M2M communication between protection relays considering the IEC 61850-90-5 based Generic Object Oriented Event (GOOSE) protocol
- A Carrier Sense Multiple Access with Collision Avoidance (CSMA-CA) based channel access technique for distribution grid M2M devices.

The second application relating to Research Question 1 focuses on modeling the communication load by taking the load supply profile into consideration. Communication loads for a majority of SG applications depend on the load supply profile of the grid. For example, the communication load for load control applications will increase during the peak hours and for EV charging applications will increase during off-peak hours (assuming most vehicles will be charged at night using domestic charging facilities). Hence, in order to accurately determine the communication requirements for such applications, it's important to develop application models that will consider inputs of both power system and communication network domains. With this motivation, a network controlled V2G load management scheme was developed and evaluated. The main outcomes include:

- A heterogeneous communication network architecture for SG distribution domain based on

WiMAX-WLAN

- An energy scheduling algorithm for efficient admission control process
- Variable energy budgeting within a specific timeframe
- Flexible data aggregation to reduce signaling and protocol overheads

The third outcome of Research Question 1 concentrates on handling the random-access load generated from a large number of M2M devices. In SGs, apart from the perennial random-access load from the time-triggered applications, when a large number of M2M devices try to access the network simultaneously after a grid event, the number of collisions can be too high in the ranging channel [31]. This results in the devices re-trying to access the network which in turns creates even more collisions. Without mechanisms to handle the network access bursts, the high access load could congest the entire ranging channel. In addition to the prolonged access delay, a congested ranging channel can exponentially increase the power consumption of the contending devices due to multiple retries. Therefore, it is imperative to develop a custom entry/re-entry procedure for M2M devices in SGs to reduce access latency, power consumption and maximize utilization of available ranging resources. The main outcomes from this study include:

- A smart ranging scheme that can provide contention-free network access to the periodic M2M applications in a SG.
- An analysis of random access success rate, access delay, and access throughput.

1.5. Research question 2 and contribution

Research Question 2: What would be the SDN-based WSN communication framework to deal with a large number of M2M devices in a NAN subnetwork?

This section discusses the contribution resulting from Research Question 2. The key contributions

include:

- Developed an SDN-Based SG network architecture for different types of SG applications and identified the features of an SG NAN network under the SDN paradigm. The theoretical framework of different major SG applications and SDN-based network architectures are presented in Section 2.
- Identified the key bottleneck limiting the development of innovative SG applications. The key bottleneck here is the inadequate dynamic network configuration capability. To resolve the issue, an in-depth survey of the emerging SDN paradigm was carried out. The benefit of using SDN in future SGs was thoroughly examined.
- Developed the SDN-based communication framework for SG NAN environment using WSNs. The framework includes developing flow processing techniques between the controller and switch. Two different types of flows named as reactive and proactive flows have been proposed to handle delay tolerant and delay sensitive SG applications respectively.
- Both delay sensitive and delay tolerant SG applications are considered based on their traffic characteristics to analyze the feasibility of the SDN-based NAN network communication.
- Modeling of a smart SDN application layer for the SG distribution grid, based on the SDN control plane and data plane characteristics.
- Development of a smart application classifier algorithm for the SDN switch.
- Application-centric traffic modeling for SDN-enabled NAN.

To address Research Question 2, a comprehensive communication framework for SDN-based NAN communication is proposed. Different types of SG applications have been considered based on their traffic characteristics. Network performance of the SDN-based NAN has been thoroughly analyzed to

validate the feasibility of the framework. Smart algorithms have been developed and introduced in the properties of WSN at the application layer to accommodate the SDN features.

1.6. Research question 3 and contribution

Research Question 3: How to maximize the performance of the SDN-enabled NAN via optimizing the number of distributed controllers and switches?

This section discusses the contribution resulting from Research Question 3. The key contributions include:

- In an SDN-based NAN, a group of IEDs and smart meters will be equipped with wireless sensors and form clusters where a single switch is responsible for each cluster. In this context, it's important to identify the optimal number of switches that will be deployed in the distribution grid to maximize the network throughput and efficiency (e.g. packet success rate). Also, to establish robust communication infrastructure and to achieve enhanced control via SDN controllers, intelligent implementation of distributed controllers in the control plane is essential. A novel mathematical model is proposed to determine the minimum number of controllers and switches that can serve the proposed framework with maximum efficiency.
- Identified the parameters and performance matrices that needed to be considered while developing the analytical model. Flow processing time of a single controller is a key factor in determining the optimal point while serving a large number of M2M devices within an SDN NAN network. The total processing time is depending on three parameters - flow request delay, associated communication delay, and flow request-response delay. Flow request delay is the period consumed by the switch whilst it asks the controller for instructions on how to handle the flow. Communication delay is a summation of the storing and forwarding delay at the switches along the communication path and the propagation delay. Lastly, the flow request response time is the time taken by the controller as it processes the incoming flow request

packets.

- An application-centric model is developed by incorporating traffic characteristics and load supply profile. A smart load scheduling algorithm based on a linear prediction algorithm is proposed that optimally balances the daily load curve by valley filling through coordinated PEV charging. To have efficient coordination among power grid controllers, charging stations and PEVs, a novel Software Defined WSN (SDWSN) is proposed and used to model the end-to-end SG NAN network architecture. The robust network architecture is scalable with enhanced controllability and manageability. The key feature of SDN, decoupling the control and data planes, is exploited to provide flexible network service provision while supporting innovative applications such as G2V.
- Smart traffic models are developed for AMI application within the SND enabled NAN domain. The main motivation behind this contribution is to test the feasibility of the proposed communication framework while implementing optimized number of distributed controllers. Simulation outcome demonstrates excellent outcome in terms of achieving the required performance metrics (delay and success rate).

1.7. List of publications

1.7.1. Conference Paper

1. **N. S. Nafi**, K. Ahmed, M. Datta and M. A. Gregory, "A novel Zigbee based pilot protection scheme for smart distribution grid," *Australasian Telecommunication Networks and Applications Conference (ATNAC)*, Southbank, VIC, 2014, pp. 146-151. doi: 10.1109/ATNAC.2014.7020889
2. **N. S. Nafi**, K. Ahmed and M. A. Gregory, "A novel vehicle to grid load management scheme

based on WiMAX-WLAN in SGs,” *2015 IEEE Wireless Communications and Networking Conference (WCNC)*, New Orleans, LA, 2015, pp. 2149-2154. doi: 10.1109/WCNC.2015.7127800

3. **Nazmus S. Nafi**, Reduan H. Khan, Khandakar Ahmed, Manoj Datta, Mark A. Gregory, “A novel WiMAX ranging scheme for periodic M2M applications in SG,” *International Telecommunication Networks and Applications Conference (ITNAC)*, vol., no., pp.250-255, 18-20 Nov. 2015, doi: 10.1109/ATNAC.2015.736682
4. **N. S. Nafi**, K. Ahmed, M. Datta and M. A. Gregory, “A novel software defined wireless sensor network based grid to vehicle load management system,” *2016 10th International Conference on Signal Processing and Communication Systems (ICSPCS)*, Gold Coast, QLD, 2016, pp. 1-6. doi: 10.1109/ICSPCS.2016.7843361
5. Khandakar Ahmed, **Nazmus S. Nafi**, Waleed Ejaz, Mark A Gregory, Asad Masood Khattak, “A Novel Framework for Software Defined Wireless Sensor Networks,” *VTC-2017-Fall*, Toronto, Canada, 2017.

1.7.2. Journal paper

1. **Nazmus S. Nafi**, Khandakar Ahmed, Mark A. Gregory, Manoj Datta, “A survey of SG architectures, applications, benefits and standardization,” *Journal of Network and Computer Applications*, Volume 76, 2016, Pages 23-36, ISSN 1084-8045, <http://dx.doi.org/10.1016/j.jnca>.
2. **Nazmus S. Nafi**, Khandakar Ahmed, Mark A. Gregory, Manoj Datta, “Software Defined Neighborhood Area Network for SG Applications,” *Future Generation Computer Systems*, October, 2017 ISSN 0167-739X.
3. K. Ahmed, **N. S. Nafi**, M. A. Gregory, “Enhanced distributed dynamic skyline query for

wireless sensor networks”, *J. Sens. Actuators Network.*, vol. 5, no. 1, Mar. 2016.

4. A. O. Arafat, A. Al-Hourani, **N. S. Nafi**, and M. A. Gregory, "A Survey on Dynamic Spectrum Access for LTE-Advanced," *Wireless Personal Communications*, 2017/08/03 2017

1.7.3. Book Chapter

1. **Nafi, N**, Ahmed, K and Gregory, M 2016, “Modelling software-defined wireless sensor network architectures for SG neighborhood area networks” *Security Solutions and Applied Cryptography in SG Communications*, IGI Global, United States, pp. 267-286.

1.8. Thesis Structure

The structure of the thesis provides a logical construction of how the PhD research questions were approached and the outcomes presented were achieved. The research objectives and outcomes are presented in six chapters.

Chapter 1 includes a brief introduction to the topic, the research challenges and objectives. This chapter also identifies the research questions and provides a summary of the contribution to knowledge. The motivation for the research is provided, including why this research is important and the research outcomes.

Chapter 2 presents a thorough literature survey on existing SG communication systems, contemporary standards, SG application requirements, traffic modelling requirements, SDN based networking and benefits of SDN in modern SG communication systems. Based on the literature review, the main literature gaps are identified on the topic.

Chapter 3 provides a detailed description of the developed traffic models and communication network architecture to support major SG applications. The major contribution against research question 1 is presented in this chapter. Section 3.2 describes the Zigbee based pilot protection scheme. Section 3.3 presents the HetNet Based V2G load management system and section 3.3 proposes a novel ranging

scheme for WiMAX scheme to accommodate large number of M2M devices. SG application models and associated traffic models with appropriate wireless access technology. The developed application models include novel algorithms and mathematical models. Furthermore, simulation models and performance analysis are included with greater detail.

Chapter 4 provides details on the SDN based WSN communication framework for SG environment. Detail communication model, packet dissemination model, smart algorithms are presented to exploit SDN concept in WSNs. Furthermore, the feasibility of the proposed SDN based NAN is demonstrated through a range of results derived from simulation and statistical analysis.

Chapter 5 presents a mathematical framework to maximize network performance with a minimum number of distributed SDN controllers. Also, an SDN based SG application model for G2V is shown with appropriate traffic models and network configuration. At the end, performance of the SDN based AMI applications are thoroughly examined by developing appropriate simulation models.

Chapter 6 draws a conclusion and highlights the overall contributions of the thesis and illuminates potential future research directions in the area of the research presented.

CHAPTER 2. Literature Review

2.1. Overview

This chapter provides a state of the art review of existing research contributions in the area of SG communication technology, application requirements, and system modeling requirements. To provide a clear understanding of SG communication systems in the different power grid domains, several end-to-end network architectures have been presented. The chapter highlights gaps in the literature that provide motivation for the research carried out. A review of the end-to-end architectures needed to support diverse SG applications is provided and this background is used to discuss the challenges of implementing the architectures to achieve maximum network efficiency. A comprehensive review of the SG standards has been included in this chapter to assist the reader identify the associated power grid and communication standards that affect SG applications.

The chapter also provides the potential benefits of using SDN for a SG environment. An emphasis is placed on utilizing SDN in the design of SG communication networks. Proposals for a SDN based end-to-end network architecture are presented as this discussion contributes to an understanding of the SDN network model for a SG environment.

2.2. SG end-to-end architecture

An understanding of the SG architecture provides a guide as to the requirements for SG communication networks. Different standardization bodies and organizations such as the DOE [1], the State of West Virginia [32] and the National Institute of Standards and Technology (NIST) [33] have developed conceptual SG architectures. However, the IEEE 2030-2011 standard has been broadly accepted as the first industry standard with a SG architecture, and configuration and interoperability requirements [34]. Within the standard, an operational model called the SG, and Interoperability Reference Model (SGIRM) is proposed to deal with the interoperability issues among different components of the communication network, power system, and information technology platform. The SGIRM provides

a guide to communication between SG generation, transmission, and distribution domains [35]. An architecture model of the End-to-End communications network based on the IEEE 2030 standard is shown in Figure 2.1.

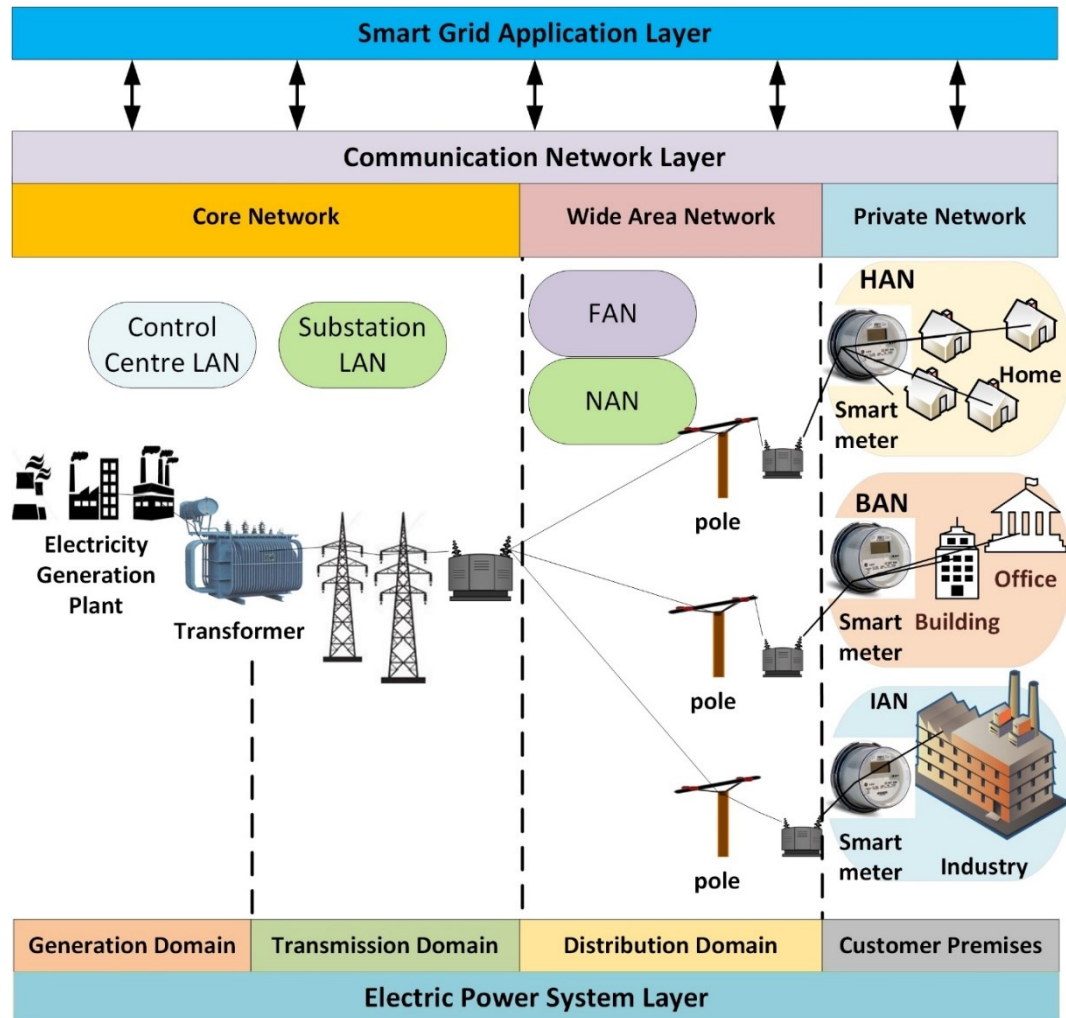


Figure 2.1 SG end to end network architecture

Modern SGs can be represented in three layers called the Electric Power System Layer, Communication Layer, and Application Layer. Interestingly, there could be numerous applications such as Automatic Meter Reading (AMR), AMI, DRM, Outage management, EV charging, Asset Management (AM), pilot protection [36] and fraud detection developed and deployed via the Application Layer. Advanced intelligent modeling of the applications could resolve crucial interoperability issues. The Electric Power Layer comprises four domains including the generation domain, transmission domain, distribution domain and customer domain. A key challenge for SG in

this layer is to provide two-way power flow between the different domains to balance energy demand and supply. The core of an SG exists in the Communication Layer and provides interconnections between all of the devices and corresponding systems.

At present, in the generation and transmission domain of the power system, legacy communications infrastructure is already in place to establish communications between the large substations. These substations are connected to the utility control center and third-party networks mainly via a high bandwidth backbone network using Digital Subscriber Line (DSL), fiber, or cable. The distribution domain is typically a large geographical area that contains a large number of substations, feeder equipment, storage facilities, distribution assets and end-users. WANs connect the infrastructure with the control center. Additionally, ‘last mile’ connectivity is also provided to customer premises to support various applications within the HAN, BAN, and IAN. Hence, to enable a grid wide monitoring and control application, functionally the WAN remains a hub for the end to end SG network as it connects all of the domains of the Electric Power Layer. Figure 2.2 shows the logical architecture of a WAN. Table 2.1 summarizes the bandwidth and latency requirements for several critical SG applications.

Table 2.1 Latency and bandwidth requirement for different SG applications [8]

<i>Application</i>	<i>Bandwidth</i>	<i>Latency</i>	<i>Payload (bytes)</i>	<i>Reliability</i>
<i>Electric Vehicles (V2G, EV charging)</i>	9.6-56kbps	2s – 5 min	255	>98%
<i>DR</i>	14-100kbps	500ms-1min	100	>99.5%
<i>Meter reading</i>	10Kbps to 128Kbps	2-15s	200	>98%
<i>Overhead Transmission Line Monitoring</i>	9.6-56kbps	15-200 ms	25	>99.5%
<i>Substation Automation</i>	9.6-56kbps	15-200 ms	25	>99.5%
<i>Outage management</i>	56kbps	2s	25	>98%
<i>Distribution Automation (DA) Periodical</i>	9.6-56kbps	25 _ 100 ms	150-200	>99.5%

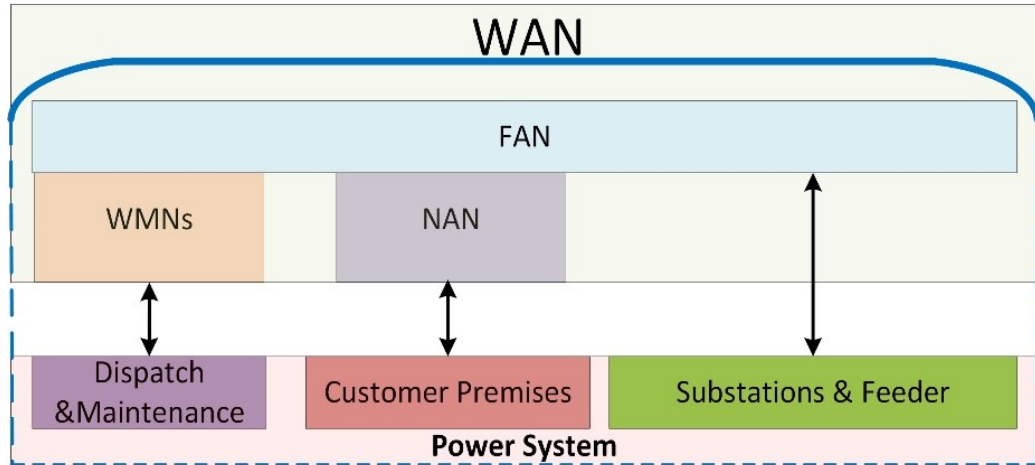


Figure 2.2 Logical architecture of a SG wide area communications network

2.3. Neighborhood Area Network

The NAN connects customer premises to utility control centers via the AMI network. The primary functional device of an AMI is the Smart Meter, which supplies consumption information and performs quality monitoring. It can also be used as an interface for energy control when used in the HAN and exchange information via the AMI system. The AMI system supports various types of intelligent SG applications such as DR, DERs, EV charging, and energy consumption in home displays. The network topology for a NAN is shown in Figure 2.3 where all of the smart meters are connected to a Data Aggregation Point (DAP) that accumulates all the data received and transmits the data to a control center.

It's important to classify the required communication technology suitable for SG applications within NAN and WAN. According to [37], wireless communication may be the only practical solution to support last mile communications in the distribution domain, which provides connectivity from smart meters to the AMI access points. Hence, to implement wireless communication network technologies in SGs, the IEEE 802.15 Task Group 4g (TG4g) was founded in December 2008 to define the Medium Access Control (MAC) and physical layer (PHY) protocols based on the IEEE 802.15.4 standard for wireless smart utility networks (SUNs) [38]. In this context, it would be interesting to investigate the possible exploitation of TV White Space (TVWS) cognitive radio to enable M2M communication in

the NAN domain. TVWS has been extensively studied [39] specifically for SG applications and in general as a promising communication technology for smart meters. It can be a viable, although not yet fully standardized, solution for the SG ecosystem.

TG4g's key objectives are to provide a global standard to support large SG network applications. SUNs support large and geographically diverse networks with minimal infrastructure, potentially connecting millions of fixed endpoints.

2.4. Field Area Network

In a power system distribution domain, high voltage electricity is converted to low voltage electricity via a step-down transformer to supply various users including commercial, industrial and home users. To perform various substation automation functions an adequate number of Remote Terminal Units (RTUs) along with Phasor Measurement Units (PMUs) and Intelligent Electronic Devices (IEDs) will be required throughout the SG distribution domain. In the SG distribution domain, the distribution feeders could be used as a point of common coupling (PCC) for the connected DERs and microgrid components. Also, installing wireless sensors along with the feeder lines, poles and transmission towers would be required to develop distribution supervisory applications. Exchanging information between the distribution substations, feeder level equipment, and applications would be the primary task of the Field Area Network (FAN).

The FAN is a communication network connecting the backhaul of a utility service provider to any particular service point of the distribution grid. Usually, with a combination of various collectors, data concentrators, and access points, a FAN provides the communication link between the substation segment and customer premises. Data collectors or sensors are connected to a centralized gateway via highly robust, reliable, low bandwidth FAN channels. At present, the International Electromechanical Commission (IEC) 61850 standard is widely used for substation and distribution automation (DA) within the FAN and provides interoperability between IEDs and M2M communication. Based on the

IEC 61850 protocol, the FAN latency requirements for mission critical data can vary between 3 to 10 ms [40].

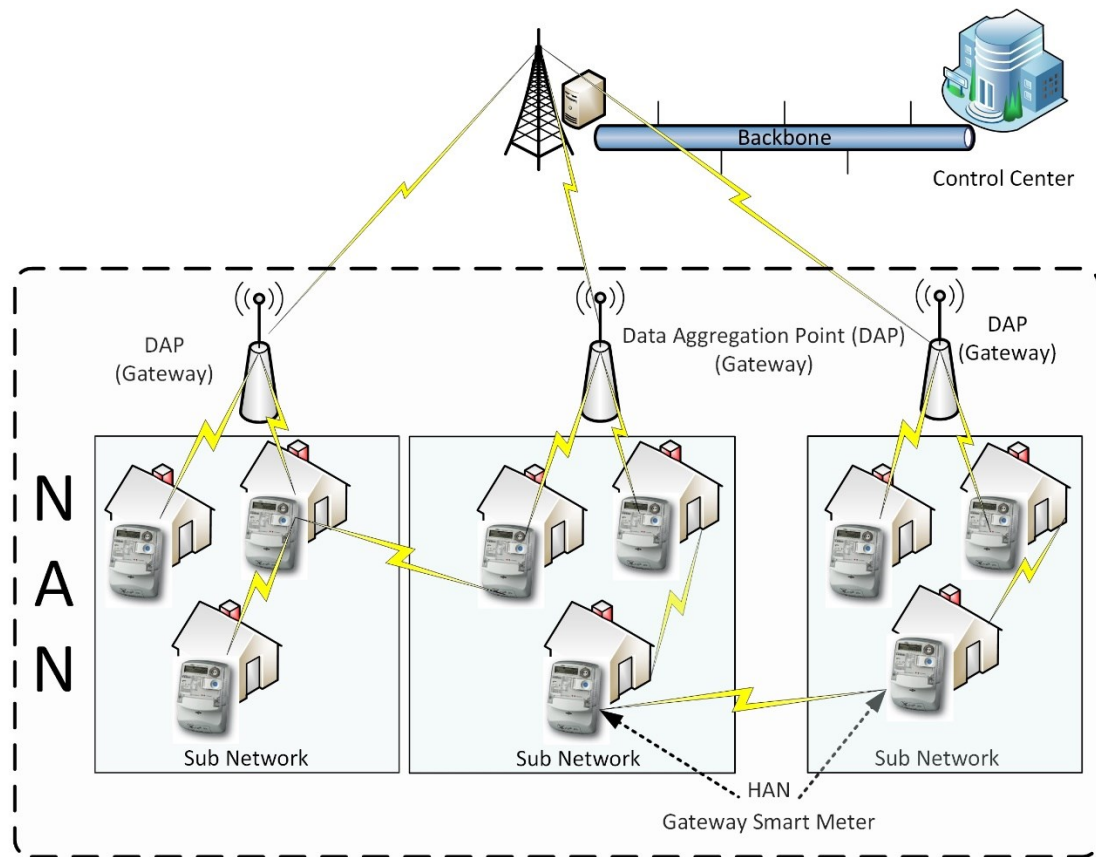


Figure 2.3 NAN Network topology

2.5. Workforce Mobile Network

The Workforce Mobile Network (WMN) is used by the utility for maintenance purposes and to carry out daily operations. SG applications can be added to the WMN, for example, V2G or G2V load management capable systems and smart vehicles with power that might be returned to the grid using location update services via tracking and navigation based on the Global Positioning System (GPS) [41]. Through the WAN, WMNs may access both the NAN and FAN to collect various types of information from equipment installed at customer premises. IEEE 802.11s is devoted to the architecture and protocols of WMNs because the communication requirement of WMN will be similar to non-M2M communication services including the Internet, voice or video applications [42].

2.6. SG standard

As a widely accepted SG standard, IEEE 2030 could be regarded as the major recent standardization effort. It defines the end to end SG architecture by integrating power systems with communications and information technology [43]. The IEEE P2030.1 and IEEE P2030.2 standards add to the detail provided in the IEEE P2030 standard. IEEE P2030.1 defines a knowledge based addressing terminology, mechanism, devices, and planning requirements for EVs and ITS applications. IEEE P2030.2 covers discrete and hybrid energy storage systems integrated with the electric power infrastructure [44]. Also, IEEE 1547 specifies the standards to interconnect distributed resources and renewable energy sources with the electricity grid.

Substation	LAN IEEE 1815/IEC 61850		Wireline	Wireless
Wide Area Network (WAN)		Core/Metro/ Backhaul Network	IEEE 802.1 IEEE 802.3	IEEE 802.16d/e IEEE 802.20 IEEE 802.22
			IEEE 802.1 IEEE 802.3 IEEE 1901	IEEE 802.11 IEEE 802.15.4 IEEE 802.16
NAN/FAN			IEEE 802.1 IEEE 802.3 IEEE 1901	IEEE 802.11 IEEE 802.15.4
Smart Meter	IEEE SC31 (1377, 1701, 1703, P1704)		IEEE 802.1 IEEE 802.3 IEEE 1901 IEEE 1901.2 IEEE P1905.1	IEEE 802.11 IEEE 802.15.4
HAN/BAN/IAN				

Figure 2.4 Mapping of the IEEE standards with the SG architecture

As a part of the SG Standardization process, the IEEE has released several other standardized protocols. Figure 2.4 shows the effort undertaken to map the SG protocol standards and Table 2.2 summarizes the SG standardization effort carried out by various organizations in different regions of the world.

The International Telecommunication Union Standardization Sector (ITU-T) has established a focus group called the SG Focus Group (SGFC) to develop recommendations, evaluate the impact of SG standards and strengthen the relationship between the ITU-T and power grid authorities. The

International Standardization Organization (ISO) has put an effort into developing SG standards for home electronics architectures (defined by ISO/IEC 14543-3) [45], and smart building design and control systems (defined by ISO 16484-5) [46]. Also, Standards Australia (SA) has been commissioned by the Australian Department of Resources, Energy and Tourism in June 2011 to support SG in Australia [47]. There are a few other national and international standardization efforts by different agencies including the IEC, NIST, ANSI, CIGRE, ISO, and ESO specifying a broad range of SG attributes [47].

Table 2.2 SG standardization in different regions of the world

<i>Location</i>	<i>SG standardization Organizations</i>
<i>Australia</i>	Standard Australia [47]
<i>The United States of America</i>	NIST [11] American National Standards Institute (ANSI) [48]
<i>European Countries</i>	European Standardization Mandate M441 Smart Meter Co-ordination Group [49] European Committee for Standardization (CEN) European Committee for Electro-technical Standardization (CENELEC) European Telecommunications Standards Institute (ETSI) SG Standardization Mandate M/490 European Standardization Organizations (ESOs) [50]
<i>Japan</i>	Japanese Industrial Standards Committee (JISC) [50]
<i>China</i>	State Grid Corporation of China [51]

The field of interest and application requirements identified in the approved IEEE standards are further classified as shown in Table 2.3. In the United States of America (U.S.A.) NIST [33] and ANSI [48] participate in the standardization effort. The aim of the U.S.A. initiative is to provide SG standardization that focuses on interoperability, reliability, security and system maintenance. So far, NIST has identified 75 SG standards, developed a theoretical SG architecture model and identified priorities for additional standards including SG related cyber security and SG action plans [33].

Table 2.3 Approved IEEE standards

<i>Field of Interest</i>	<i>Approved standards</i>	<i>Field of Interest</i>	<i>Approved standards</i>
Interoperability	IEEE Std 2030-2014 [44] IEEE Std 1377-2012 [52] IEEE Std 1701-2011 [53] IEEE Std 1702-2011 [54] IEEE Std 1703-2012 (Local Area Network-LAN/WAN) [55]	Networking and communications	IEEE Std 802-2012 [56] IEEE Std 802.1AB-2009 [57] IEEE Std 802.1AE-2006 (MAC) Security [58] IEEE Std 802.1AR-2009 [59] IEEE Std 802.1AXbk-2012 [60] (Link Aggregation) IEEE Std 802.1Xbx-2014 [61] (Port-Based Network Access Control) ISO 8802-2 IEEE 802.2 (Logical LinkControl) [62] IEEE Std 802.3bj-2014 (Ethernet) [63] P802.11-REVmb/D12 (PHY)(MAC) [64] IEEE Std 802.15.1-2005 (LAN to MAC info exchange) (MAC, PHY) [65] IEEE Std 802.15.4m-2014 (MAC & PHY for LR WPANs) [66] IEEE Std 802.15.4e-2012 (MAC for LR-WPANs) [67] IEEE Std 802.15.4g-2012 (PHY for LR-WPANs) [68] IEEE Std 802.16-2012 (Air Interface for Broadband Wireless Access Systems) [69] IEEE Std 802.16n-2013 (Higher Reliability Networks) [70] IEEE Std 802.16p-2012 (M2M application) [71] IEEE Std 802.16.1-2012 (WirelessMAN-Advanced) [72] IEEE Std 802.16.1a-2013 (Higher Reliability Networks) [73] IEEE Std 802.16.1b-2012 [74] IEEE Std 802.20-2008 (Vehicular Mobility) [75] IEEE Std 1901-2010 (Power Line Networks) [76]
Cyber Security	IEEE Std 1402-2000 (Electric power substation physical and electronic security) [77] IEEE Std 1686 - 2013 (Substation Intelligent Electronic Devices) [78] IEEE Std 1711-2010 (Cryptographic Protocol for cyber security of	Substation and DA	IEEE Std 1379-2000 (Communication between RTUs & IEDs at substations) [80] IEEE Std 1615-2007 (Network Communication in Substations) [81] IEEE Std 1646-2004 [82] (Time Performance Requirements for Electric Power Substation Automation) IEEE Std 1815-2012- Distributed Network Protocol (DNP3) [83] IEEE Std C37.94-2002 [84] IEEE Standard for N Times 64 Kilobit Per Second Optical Fiber Interfaces Between Teleprotection and Multiplexer Equipment IEEE Std C37.111-2013 [85], Common Format for Transient Data Exchange (COMTRADE) IEEE Std C37.118.2-2011 [86] (Synchrophasor Data Transfer)

	substation serial links) [79]		<p>IEEE Std C37.1-2007 [87] (SCADA and Automation Systems)</p> <p>IEEE Std C37.231-2006 [88] (Microprocessor-Based Protection Equipment Firmware Control)</p> <p>IEEE Std C37.232-2007 [89] (Naming Time Sequence Data Files)</p> <p>IEEE Std C37.232-2011 [90] (Naming Time Sequence Data Files (COMNAME))</p> <p>IEEE Std C37.236-2013 [91] (Protective Relay Applications over Digital Communication Channels)</p> <p>IEEE Std C37.238-2011 [92] (Use of IEEE Std 1588 Precision Time Protocol in Power System Applications)</p> <p>IEEE Std C37.239-2010 [93] (Event Data Exchange (COMFEDE))</p> <p>IEEE Std C37.244-2013, IEEE Draft Guide for Phasor Data Concentrator Requirements for Power System Protection, Control, and Monitoring</p>
<i>Electric power infrastructure</i>	IEEE P2030.100 [94]	<i>Renewables</i>	IEEE Std 1547.3-2007 [95] IEEE Guide For Monitoring, Information Exchange, and Control of Distributed Resources Interconnected With Electric Power Systems
<i>AMI</i>	IEEE Std 1377-2012, Utility Industry Metering Communication Protocol Application Layer Standard (End Device Data Tables) [52]	<i>Device data tables</i>	IEEE P1703 [96] Draft Standard for Utility Industry End Device Communications Module
<i>Power quality and energy efficiency</i>	IEEE Std 1159.3-2003 [97] IEEE Recommended Practice for the Transfer of Power Quality Data	<i>EVs</i>	<p>IEEE Std 1901-2010 [76]</p> <p>IEEE Std 1901.2-2013 [98]</p>

For electrical substation automation, the IEC 61850 standard has been widely adopted in different parts of the world in recent years [99]. SG security related issues are defined in the IEC 62351 standard [99]. The standards play a vital role in the future transition of electrical distribution grids to SGs. To integrate communication technology along with the distribution system, the standards can be considered as basic block to derive improved technology solutions. A summary of the IEC standards and their functional domain is shown in Table 2.4 [51][100].

Table 2.4 IEC standards

<i>Standard</i>	<i>Point of Interest</i>
IEC 61970/61968	Common Information Model (CIM) [101], [102]
IEC 61850	Substation Automation Systems (SAS) and DER [103]
IEC 62351	Security for the SG [104]
IEC 62357	TC 57 Seamless Integration Architecture [105]
IEC 60870	Communication and Transport Protocols [106][107][108]
IEC 61400-25	Communication and Monitoring for Wind Power Plants [109]
IEC 61334	DLMS [110]
IEC 62056	COSEM [111]
IEC 62325	Market Communications using CIM [112]

SGs would permit a significant amount of raw data to be collected from the end users. It is quite clear that there are security and privacy threats to the user's personal data and behavior profile. The existence of SGs could be jeopardized if the security and privacy issues are not carefully handled. A large monitoring and sensory device network would widen the horizon of possible intrusions and attacks. For example, an inefficient user authentication system may result in meter data manipulation. A possible protective measure to increase SG security and privacy could be achieved by increasing the capacity available to update network configuration and monitoring during operations. Software engineering approaches to handle SG security and privacy issues are discussed in [113]. Also, an agent based protective scheme is presented in [114] to treat different types of cyber-attacks on SG.

2.7. SG Applications and Communication Requirements

2.7.1. Advance Metering Infrastructure

To exchange information between the end users and the utilities AMI creates a two-way communication network comprised of advanced sensors, smart meters, monitoring systems, computer hardware, software, and data management systems. Within an AMI, smart meters are used to collect meter data or information on events via a periodic message exchange. AMI features and capabilities include a Meter Data Management System, Consumer Awareness systems, Interactive Services for Regulation of Energy Demand, systems to assist with avoidance of Electricity-related fraud and time accurate billing services [115]. There is a significant amount of literature available on AMI and AMR

applications for SGs [116][117][118][119]. Also, standards such as ANSI C12.19-2008 [120], IEEE 1377 2012 [52], and IEC 61968-9 [102] define and specify the technical requirements for the physical implementation of AMI applications. The IEC 61968-9 [121] standard provides a more generic platform to cover various aspects of AMI based SG applications (e.g. meter connection status, meter data, outage management, etc.).

Figure 2.5 Logical representation of SG Automatic Metering Infrastructure shows a detailed AMI architecture that includes the use of a data collection unit. Based on an RF/Zigbee communications network, smart meters act as an aggregator and send data to the data collection unit where a system controller transfers the aggregated data to the Meter Data Management System (MDMS). The MDMS processes incoming raw data to generate useful statistics and provides energy usage information for customers.

The primary component of an AMI system is the smart meter which sends meter readings in a scheduled manner to the MDMS. Meter reading data can be used for verification applications such as outage extent verification, outage restoration verification, billing applications and event based alarm applications such as meter health status (e.g. configuration and connection status), and voltage distortion (e.g. high or low).

An AMI has to deal with a large amount of data, as it collects information from all of the active meters within the network coverage area. According to the SG Priority Action Plan 2 (PAP2) report, released by the U.S. NIST, meter density is 100, 800 and 2000 per square kilometer for rural, suburban and urban areas respectively [122]. According to [123] in the event of widespread power outage affected smart meters need to send an alarm to the control center within a few hundred milliseconds. It's highly challenging to send the 'last gasp' message within the delay boundary as all of the smart meters are bound to operate without battery power relying on capacitive charge only. Thus, for a large number of smart meters, providing network access within a short period is a crucial requirement of an AMR

application [124].

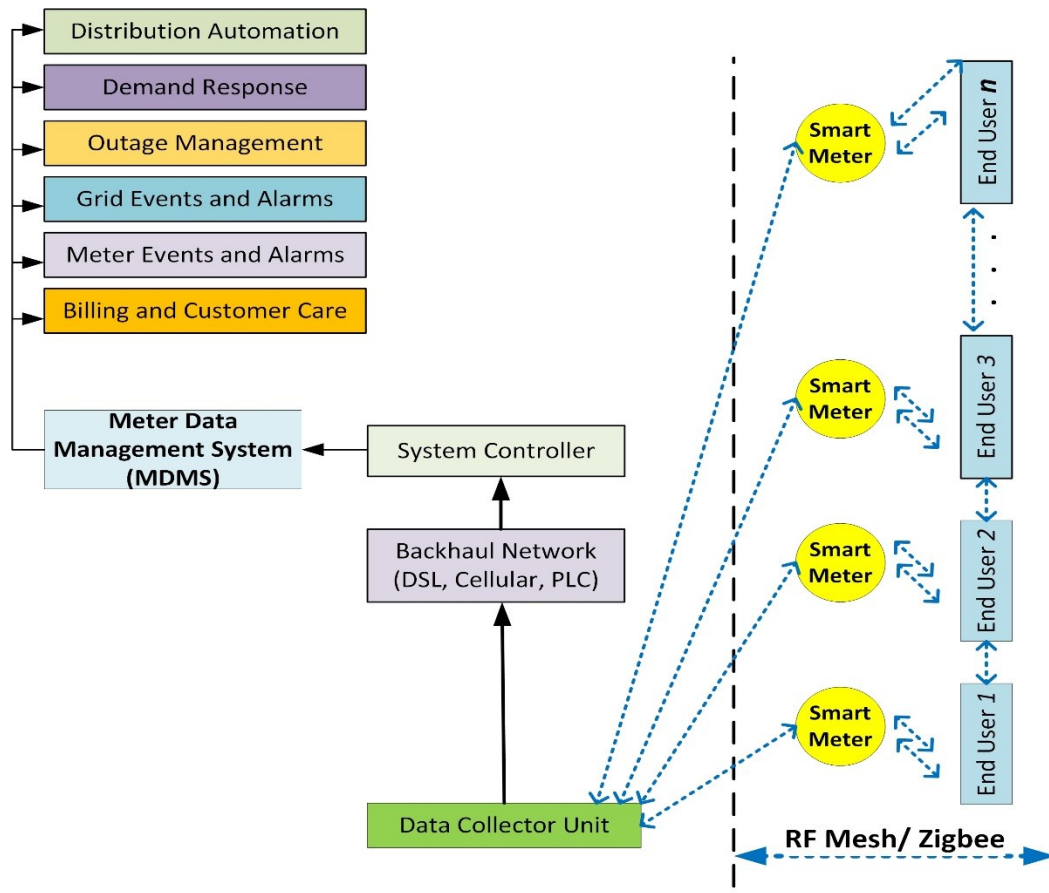


Figure 2.5 Logical representation of SG Automatic Metering Infrastructure

2.7.2. Demand Response

DR is the mechanism used to reduce power generation peak demand through consumer participation and by optimally balancing or controlling their energy consumption or demand load. By optimally balancing energy consumption and power generation, either through adaptive pricing or by applying various load management techniques DR can offer efficient, reliable and cheaper power to consumers. Studies found in the literature [123][124] explain various types of DR programs such as incentive-based programs (IBP), priced based programs (PBP), real-time pricing (RTP), time of use (ToU) rate, critical peak pricing (CPP), extreme day pricing (EDP) and extreme day CPP (ED-CPP). In DR programs, end users take part in the energy business by changing their energy consumption behavior concerning variable energy price units rather than fixed price units which result in profits by both the utilities and customers [125]. There are various types of DR based on implementation and long term

or short term outcomes. A summary of the available DR programs is shown below.

Time of Use. ToU is a DR program where billing months are segmented into hourly windows that are assigned a different price based on production cost. A price signal is provided to consumers to minimize energy usage during peak periods. For example, ToU could include daily peak and off peak pricing. Variable pricing could be extended to differentiate between weekdays and weekends. Also, seasonal pricing could be incorporated in the ToU for implementing DR programs.

Critical Peak Pricing. CPP is an optional scheme that is often combined with on peak and off peak ToU periods and may not be applied during specific periods. CPP will be in operation only when the Load Serving Entity is serving a load demand that is deemed to be critical. The critical state could include reaching maximum capacity, and there could be multiple CPP events on a single day.

Peak Time Rebate. In a Peak Time Rebate (PTR) DR program, a customer can be paid to not use electricity during the CPP hours. A notice before initiating the event or during the event would be sent to the customers participating in the DR program. The total demand load reduced by the customers during CPP hours is measured by comparing usage with the basic demand load at the same time on a typical day. Based on the amount of demand reduction, the customers could claim a rebate.

Real Time Pricing. In a Real Time Pricing (RTP) DR program, customers are provided with the day ahead or an hour ahead pricing of energy units. The energy price units determine energy usage limits where the customers volunteer to minimize energy consumption to maximize their savings. Participants of this program are usually charged for exceeding the assigned Customer Baseline (CBL) load curve. Also, customers receive a reward in term of credit if the usage remains below the CBL.

Direct Load Control. When Direct Load Control (DLC) becomes unavoidable, it is necessary to initiate load reduction, such as load shedding to maintain system reliability and cope with high production costs. DLC provides credits to participants for reducing load during these events. There are

two types of load reduction mechanism: (1) the DLC program maintains direct control over consumer loads that may be shed, and (2) participants maintain control over loads that may be shed. If a participant does not shed a load that is part of a DLC program, penalties may apply.

Remote Load Control. The Remote Load Control (RLC) DR program is more advanced and household appliances are remotely controlled using an advanced algorithm to reduce demand load. An M2M communication infrastructure is used, and price signals are sent to the automated electrical home appliances so that time of operation can be scheduled based on the energy unit price. There are three types of loads defined for RLC.

- A. **Interruptible Loads.** This load can accept an interruption and have its operation shifted to other time to avoid a peak period. Electrical appliances, like water pumps, dish washers, and dryers, can be shifted to a different time slot to avoid peak periods. A load control command is required to initiate the interruption and the operation time shift.
- B. **Reducible Load.** A reducible load indicates that operations can be reduced for a specific amount of time. For instance, an air conditioner can reduce its energy consumption and maintain a minimum threshold of comfort level during a peak time if the temperature is set to high for that period. Hence, periodic interactions are required from the remote DR server at the time of load management.
- C. **Interruptible Load.** Interruptible loads can be shed over a peak period based on the run time cycle length. For example, if the run time cycle is 60 minutes, then 50% reduction will result in a 30-minute cycle during a peak hour. Two control signals are required to initiate and complete the cycle limit.

Some factors affect DR program operations including regulations, energy pricing, environmental requirements, and control signal communications. For example, during summer the wholesale

electricity price may increase as there will be more demand for air conditioning. In this case, there is likely to be multiple RLC sessions initiated by the DR controller. Hence, this will result in a high SG communication traffic load, and a robust communication network will be essential. Additionally, in the case of price based DR programs, remote servers utilize multicast signaling to the subscribed customers. Usually, transmission of these traffic loads are delay tolerant, but at the same time, they are very sensitive to packet loss. However, according to [126], DRM programs require a bandwidth of 14 to 100 Kbps per device to provide system continuity and to remotely control smart appliances for peak demand management.

The communication loads vary with the type of DR program. DR programs based on price have relatively lower communication traffic load compared to the other RLC programs as they require increased information exchange. Among the RLC programs, the Interruptible Load program requires a lower traffic load because it involves fewer control signals to interrupt and reschedule operations. On the other hand, Partially Interruptible Load and Reducible Load programs require higher communication traffic as more control signals are exchanged.

2.7.3. Substation Automation

In SGs, substation automation via M2M communication facilitates advanced monitoring, protection and control functions for the transmission and distribution substations (e.g. protection signals to relays) and feeder equipment (e.g. automatic reclosers and switches for fault isolation). Widely adopted standards for this part of the power grid are the IEC 61850 and Distributed Network Protocol: version 3 (DNP3) or IEEE 1815 standards. The IEC 61850 standard is fairly comprehensive when it comes to defining substation automation features, including control applications and real time high-bandwidth protection. According to the IEC 61850 standard, communication between interoperable IEDs will be based on the Internet Protocol (IP) and Ethernet standards.

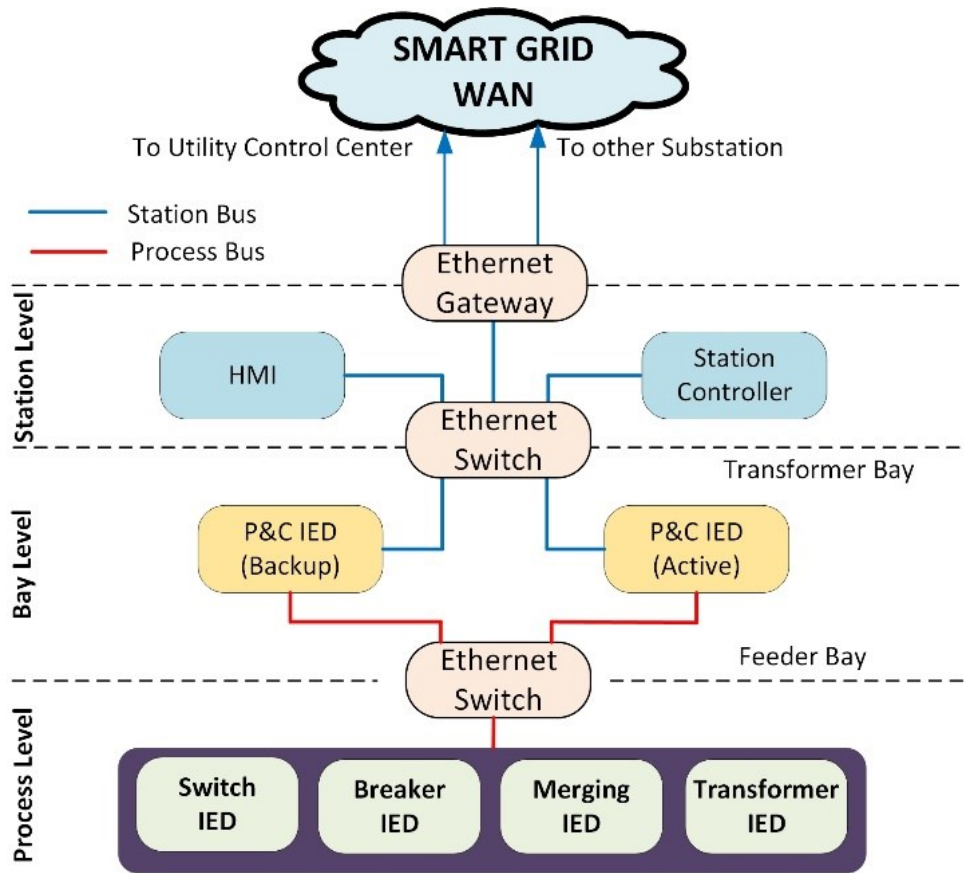


Figure 2.6 Intra Substation communication network

Additionally, to differentiate various traffic flows, five types of priority based communication services are defined:

- Abstract Communication Service Interface (ACSI)
- GOOSE
- Generic Substation Status Event (GSSE)
- Sampled Measured Value (SMV)
- Time Synchronization (TS)

Intra-substation Communications. The IEC 61850 standard covers control and communication with substation equipment and devices. Figure 2.6 shows the communication architecture of intra-substation communication which has three classified levels known as station level, bay level, and

process level. The switch yards' equipment including current transformers (CT), potential transformers (PT), input output (I/O) devices, sensors, actuators, circuit breakers, switches, and merging unit (MU) IEDs are part of the process level.

Analog voltage and current values are collected from the field CT and PTs via the MU IEDs and sent to the protection and control (P&C) IEDs at the bay level. The station level comprises the station controllers and human device interfaces (HMI). Two separate Ethernet subnetworks that are called the process bus and substation bus are defined in the IEC 61850 to facilitate QoS implementations. The process bus handles delay sensitive communication between P&C IEDs and switch IEDs, breaker IEDs as well as the emerging IEDs. Communication between different bays and station controllers is handled by the station bus. However, communication with external networks, including other substations and the utility control center occurs via a gateway to the substation.

Inter-substation Communications. Inter-substation communication or M2M communication between different IEDs in a distribution domain requires application data transmission from telemetry or sensors to an aggregator. M2M communication is based on reliable delivery of single messages within a strict delay boundary. Also, the extensive use of microprocessor-based protective relaying techniques enables development of wide area monitoring, protection and control (WAMPC) systems [127], a converging process towards a universal SG communications network [128][129][130] solution. According to IEC 61850, the type of message in the inter-substation communication is defined by the GOOSE profile. The GOOSE message can be exchanged using IP and can also support both unicast and multicast. Thus, the shift to IP based integrated SG communications networks for advanced protection and control schemes in the power transmission and distribution grid could be an important feature of inter-substation communications. However, the performance of an M2M application is evaluated in objective terms such as measurement of delay or packet arrival rate while using any wireless communication system. So, to accommodate different types of SG traffic along with the protection traffic, a wireless communication solution must be efficient and ensure high end to

end transmission reliability.

A number of proposals can be found in the literature on using digital communications to develop protective applications at the SG distribution domain [128][129][130]. [96] presents a report released by the IEEE Power System Relaying Committee (PSRC) on protective relaying applications using the forthcoming SG communications infrastructure. Clement-Nyns et al. describe the use of wireless communications media such as microwave, narrow band radio, and spread spectrum radio for pilot protection schemes [131]. Other pilot protection applications based on the IEC 61850-based GOOSE messaging are described in [132][133]. WiMAX and Zigbee based pilot protection schemes for smart distribution domain are proposed in [133][134].

Among the common protection methods, directional comparison blocking (DCB) and permissive over-reaching transfer trip (POTT) [135] are well cited in the literature as popular pilot protection schemes. The key development challenge for protection schemes on communication aspect is to transfer the GOOSE packets with the pilot trip/block signals within a specified time delay to isolate the fault otherwise the relay would trip automatically. Also, the signal should be transferred as fast as possible because the associated switch/circuit breakers will be delayed by the data communication time plus a small guard time [136]. So, to maximize the efficiency of the protection scheme, the communication delay should be minimized as much as possible. Usually, POTT operating delay is 30-35ms whereas the DCB operating delay is 80ms (including relay operation time) for a 50 Hz power system. Hence, Maciejowski [135] suggested that with a 5 ms delay for high-speed relay operation a pilot signal would have a delay budget of 25-30 ms for the communications network. Table 2.5 SG Communication specification for substation automation summarizes the communication requirements and service types of substation automation.

2.7.4. Distributed Energy Resources

DER has significantly increased due to the growing trend towards rooftop solar panels and other

renewable energy resources, including wind power. Renewable energy resources are advantageous because of lower carbon emissions, and due to decreasing installation costs, the DER are becoming more popular. However, some of the renewable energy sources require energy storage devices for low generation periods.

Table 2.5 SG Communication specification for substation automation

<i>Msg. Type</i>	<i>Application</i>	<i>Service type</i>	<i>Time boundary (ms)</i>
<i>A1</i>	Fast Message (Trip)	GOOSE, GSSE	3-100
<i>A2</i>	Fast Message (Other)		20-100
<i>B</i>	Medium Speed	ACSI	100
<i>C</i>	Low Speed		500
<i>D</i>	Raw Data	SMV	3-10
<i>E</i>	File Transfer	ACSI	>1000
<i>F</i>	Time Synchronization	TS	(Accuracy)

The additional controllable power provided by energy storage devices could be used to provide consistent supply with more reliability and capacity. However, the bandwidth requirement for extracting instantaneous information from the generation points is about 9.6 to 56 Kbps. The latency range can vary from 300ms to 2s while the reliability must be within 99 to 99.99% [126].

Required power to drive an EV ranges from 10 to 200KW, and this power is usually supplied from batteries or fuel cells. By V2G operation the stored energy can be sent back to the grid if needed. So, EVs may work like a mobile DER and the stored power of the batteries or generated power from the vehicle's kinetic energy can be supplied to the power grid. Hence by using EVs as a source of energy it would be possible to increase power generation during peak times, improve backup capacity and power system reliability. Additionally, renewable energy sources can be integrated with the V2G; the vehicle can provide sufficient back-up for renewable energy generation and act as a storage device. The communication requirement of V2G application depends on the speed of the vehicle. The authors of [136] provide the communication requirements for a parked fleet of vehicles. Wireless

communication technologies like ZigBee or Wi-Fi will support V2G applications in parking areas. For moving vehicles, mobile cellular communication is appropriate. Power transmission enhancement is an important factor for planning large scale power systems and regional transmission because the EVs introduce new types of loads to the grid. The communication bandwidth requirement for a V2G application is 5-10 kbps, and the latency requirement is up to 2s [126].

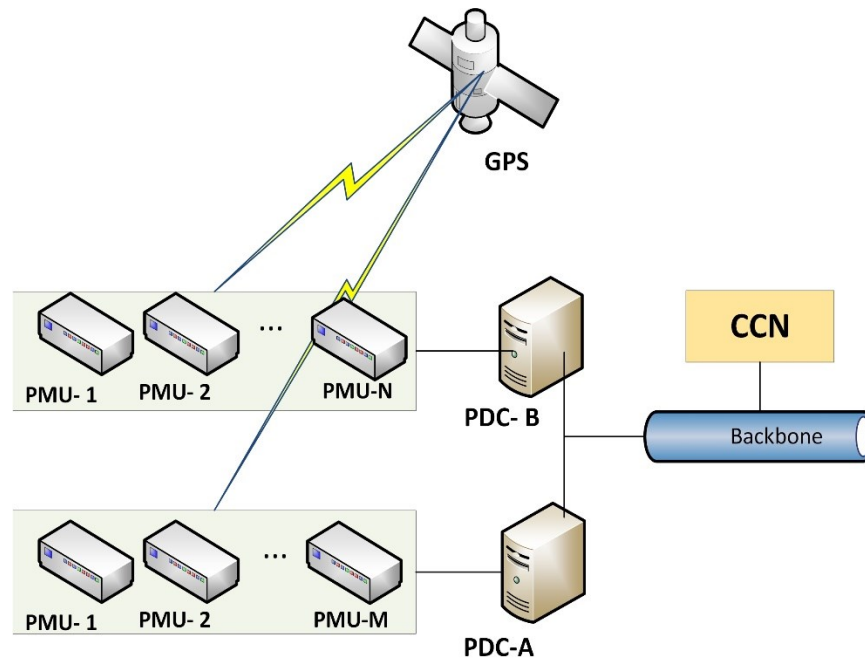


Figure 2.7 Network topology of a Wide Area Measurement System

2.7.5. Wide Area Measurement

In a Wide Area Measurement System (WAMS) the power grid status is continuously monitored, and a PMU is used to update system state informatics and real-time power quality measures. GPS data can be used to allocate a time stamp with each measurement to provide accurate real-time measurements [137]. High-resolution phase information can be obtained by the utility with precise measurement synchronization, and the utility could initiate an appropriate response within the delay bound to protect the WAN from a blackout [138]. In the existing power grid, PMUs are installed within the generation and transmission domain of the power grid considering the unidirectional power flow from generation to distribution. However, to enable bi-directional power flow and real-time system monitoring, PMUs need to be deployed at SG distribution points [139]. Figure 2.7 shows the WAMS network topology.

To build a WAMS it is essential to deploy PMUs within the regional and national power grids, and usually, a Phasor Data Collector (PDC) collects all of the measurements from a network where the PMUs are deployed. The PDC aggregates and transmits the data to the Central Control Network (CCN) location via the transit and backhaul networks.

The IEEE C37.118.2–2011 provides the PMU data communication specifications. The reporting frequency is the key factor used to determine the communication load which may vary between 10, 25 Hz and 10, 12, 15, 20, 30 Hz for a 50 Hz and 60 Hz based power systems respectively. However, the main communication requirement for WAMS applications is to establish a secure and reliable communication link between PMUs and PDC within the specific latency.

2.7.6. Distribution grid protection

A conventional power system is divided into different sections such as the generation plants, transmission networks, distribution systems and consumer demand feeders. Typically, conventional power systems were designed to support unidirectional power flow from the generation plants to the consumers. The production, transmission and distribution supply networks consist of hundreds of components, devices, control units and protection devices. With the rise of the SG concept and renewable based distributed generation, bidirectional power flow in the distribution networks is necessary. To maximize reliability and to support time varying bidirectional power flow, it is essential for the components of the power grids to exchange critical control data and work in a fully meshed manner. Therefore, SG research is focusing on upgrading the power grids to facilitate bidirectional power and communication flows utilising sophisticated state of the art electrical and communication technologies to maximize performance and reliability [133].

The distribution section of the power grid requires a reliable protection system for the distribution lines and equipment. The protection system should identify faults and ensure appropriate isolation when a fault occurs. Usually, pilot protection schemes are commonly used for FDIR purposes in the

distribution section of power grids [30]. Additionally, these schemes use high-speed peer-to-peer communication between the relays at both ends of a distribution line terminal to ensure secure and selective relay tripping. However, the challenge associated with these protection mechanisms is to deliver the fault information within a strict delay boundary through a communication channel that can transmit a binary, on/off, permissive or blocking signal. Therefore, widespread deployment of the pilot protection schemes, which have improved communication links, should provide improved reliability and performance. Among the common protection methods, DCB and permissive over-reaching transfer trip (POTT) [130] are cited in the literature as popular pilot protection schemes. In most of the dedicated intra-substation communication systems, DCB and POTT are implemented utilising traditional communication solutions based on copper cable, microwave, fiber optic cables or power line carriers, resulting in high installation and operational costs.

Inter-substation communication or M2M communication between different IEDs in a distribution network requires the transmission of application data between the sensors and other measurement devices. M2M communication is based on reliable delivery of single messages within a strict delay boundary. In recent years, peer-to-peer communication in distribution systems has been standardized as IEC 61850 [140]. According to IEC 61850, the type of message in the intra-substation communication is defined by the GOOSE profile [30]. The GOOSE message can be exchanged through IP routing and can also support both unicast and multicast techniques. Hence, for pilot protection, the IEC 61850 based GOOSE message is an appropriate choice. However, the performance of an M2M application is evaluated in objective terms such as measurement of delay or packet arrival rate while using any wireless communication protocol. So, to accommodate different types of SG traffic along with the protection traffic, a wireless communication solution must be robust and ensure end-to-end transmission reliability.

2.8. SDN based SG

2.8.1. SDN NAN Architecture utilising WSN

Many of the networking devices in the current SGs are designed to serve individual or selected applications. The main objectives of using the devices are to enable M2M communication that can be termed as hardware-centric networking. However, a hardware-centric networking approach faces challenges regarding scalability and controllability because the devices can only process a few commands. In such a scenario, it's impossible to reconfigure network settings at any emergency grid event. The non-adaptive network configuration of large M2M networks is more prone to malicious attack. Lack of a real-time grid monitoring capacity contributes to poor network QoS. Also, the network configuration is carried out through specific operating systems. Network control options become limited when only predefined commands are available. To overcome these issues, SDNs offer more flexibility by adding controller programmability. SG devices could be used more efficiently for M2M communication where more applications and protocols could be implemented in SDN based SG networks. According to [141] network control is fully programmable in SDN and is isolated from the packet forwarding mechanism. An SDN controller usually has the functionality to be the centralized controller of the network and can deploy multiple packet forwarding schemes or flows via the SDN switches. SDN has the potential for information centric networks where the network complexity could be reduced and network manageability increased [142]. Thus, SDN becomes an appropriate candidate for SG communication networks where a large number of M2M devices are needed to be controlled, monitored, and smart data aggregation is mandatory to run various types of sensitive applications. Moreover, inter-domain communication within the SG would require sophisticated packet classifier and gateways, network address translators or firewalls which could be configured in an SDN switch [143]. Figure 2.8 shows a conceptual network architecture of a heterogeneous communication network for an SDN based SG.

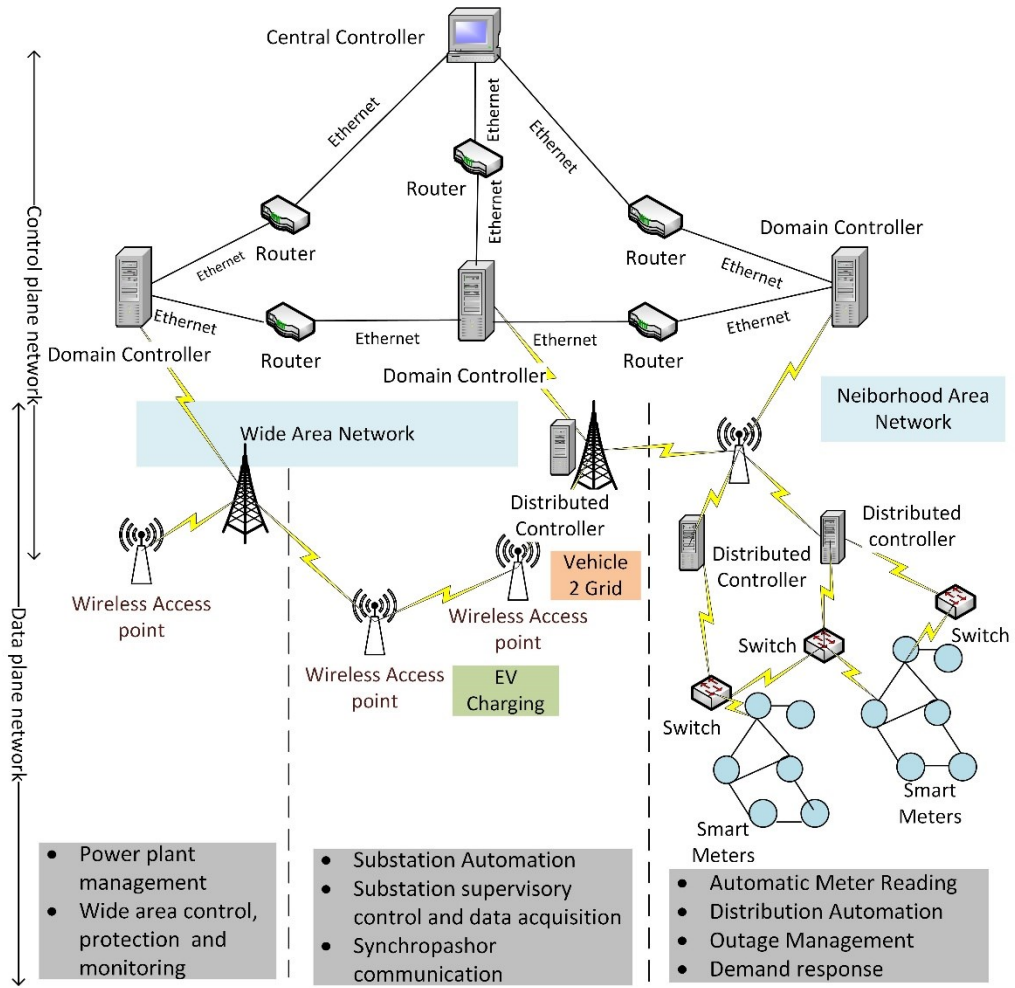


Figure 2.8 SDN based network architecture of heterogeneous communication network for SG

As shown in Figure 2.8 different domains of the SG such as Generation, Distribution or customer premises could be modeled with the SDN cross domain content based networking properties. SDN could exploit the features of information-centric networking (ICN) [144] such as content query, content-id based routing or in-network content catching to form groups of similar traffic sets and disseminate data through the SG cross-domain devices. Another advantage of using SDN in SGs would be the provision to create virtual networks. SDN overcomes the limitations of conventional virtual local area networks (VLANs) or virtual private networks (VPNs) due to its higher degree of software instruction acceptability and fast reconfiguration capability. The concept of a virtual power plant (VPP) [145] could be an extension of the SDN virtualization property in a modern SG. In the NAN, information on the power grid will be retrieved using sensor devices, smart meters and intelligent electronic devices, etc. Furthermore, a well-designed SDN control plane would utilize retrieved data

to deploy useful SG applications such as AMR, outage management and DA, etc. In the distribution grid, SG application like V2G, G2V or substation automation could be deployed via SDN based SG WAN.

According to Gungor et. al. [146] WSNs could be a potential wireless technology used in power grid sub domains. Also, to make the SG communication network more robust other wireless technologies such as WiMax and Wi-Fi could be incorporated to build a HetNet. The most common applications within a NAN are smart metering, DR and distributed automation, etc. [147]. To deploy these applications, a large number of end user devices or smart meters are installed, and several data concentrator or aggregators are required. In SG NAN the data rate varies between 100 Kbps to 10 Mbps, and the traffic can travel over 10 Km (max) [147]. Among available wireless sensor technologies, ZigBee mesh networks are widely accepted and implemented. The IEEE standards association has released the IEEE802.15.4g task group (TG4g) [148] that provide specifications to support a large number of smart utility equipment's deployed in diverse geographical topology using minimal infrastructure.

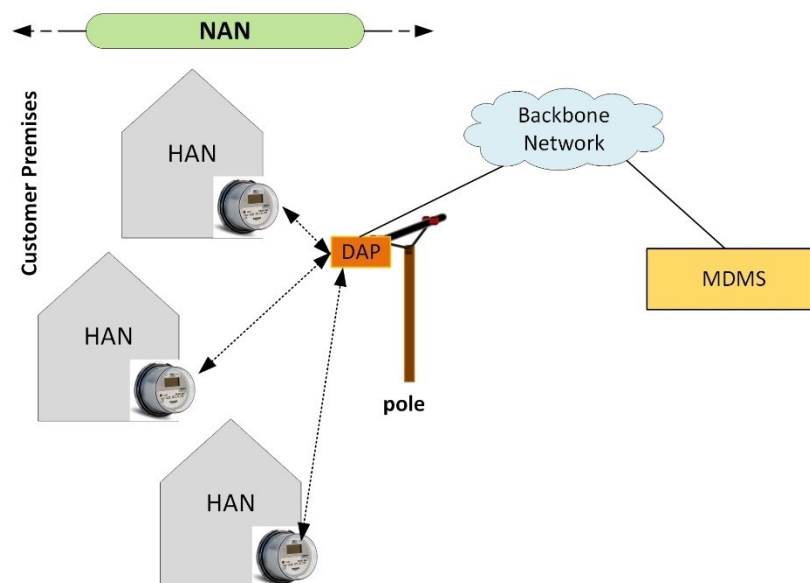


Figure 2.9 SG Neighborhood Area Network

The NAN of the SG communication network comprises of a vast number of smart meters. The NAN

can be referred to as a logical representation of AMI [149]. As a core component of a NAN, smart meters provide various types of information on the consumption and power quality and also perform a few load balancing tasks. Interestingly, private networks like the HAN can be connected to a NAN via smart meters acting as an Energy Service Interface (ESI). A number of SG applications such as Plugged in Electric Vehicle (PEVs) charging and discharging, remote load balancing and load management, synchronization of DERs, in-home consumption monitoring, and control system, etc. can be deployed via AMI infrastructure. Figure 2.9 represents the logical configuration of a NAN in an SG. A single smart meter or a DAP connected to multiple smart meters may act as an end point of the NAN. With a backbone network, the NAN is connected to the control center MDMS.

It's important to determine the appropriate communication technology when modeling the NAN. A couple of important factors need to be taken into consideration while developing the network solution for this section of the SG. In an SG AMI system, the periodicity of the packet transmission can be random, semi-periodic or fully periodic. Based on the type of application, a packet can be categorized as a delay tolerant or delay sensitive packet. In the case of a stochastic delay sensitive application, the packet needs to be delivered to the destination within a strict delay boundary with high accuracy. For a delay tolerant packet, the network reliability should be very high so that there is minimal information loss during packet transmission. While keeping the requirements above in mind, WSN can be considered to be an appropriate solution among the existing wireless solutions for modeling SG NAN as it also includes inherent support for sensors and data collection. This is due to the fundamental characteristics of WSN, where a large number of short range sensor nodes create a mesh network and collect data such as voltage, current, and frequency. The sensor nodes in a WSN operate using very low power at a minimal cost. Also, sensor nodes are small in size and could operate under extreme weather conditions with self-configuring features. While deploying the WSN nodes in a high voltage environment, it is likely that insulation would be needed and this can be either retrofitted or built into the WSN nodes. Hence, WSN can be used as a key enabler for many SG applications such as DR,

PEVs and load management at the customer premises.

The IEEE 802.15.4 Zigbee standard operates in three different frequency band and uses one channel between 868.0 and 868.6MHz in Europe (Ch 0), 10 channels between 902.0 and 928.0MHz in the USA (Ch 1-10), and 16 channels between 2.4 and 2.4835GHz worldwide, (Ch 11-26) [36]. The 2400–2483.5MHz is the only worldwide allocation of spectrum for unlicensed usage without any limitations on applications and transmitted duty cycle and provides up to 1W transmit power in spread spectrum modes in the United States. There are two types of devices specified for the Zigbee protocol including the FFD and a RFD. Based on the activity performed an FFD can act as a Zigbee coordinator router (in a multi-hop scenario). An RFD can act as an end device which does not route packets nor transfer significant amounts of data. The Zigbee protocol operating on the 2.4 GHz band uses OQPSK for chip transmission modulation. Each 4-bit symbol is mapped into a 32 chip PN sequence, and data rate can achieve up to 250Kbps in 2.4 GHz operation [150]. Possible Zigbee network topologies include star, mesh or cluster tree and depending on the application facilitate home automation, remote metering, industrial automation, active RFID asset tracking, medical and recently consumer electronics remote controls.

The channel access mechanism uses two different modes named as beacon enabled and non-beacon enabled modes. A beacon enabled Zigbee channel uses a superframe structure, and a network coordinator transmits beacons at predetermined intervals. A superframe structure is divided into two parts called the active and inactive parts where the active part consists of 16-time slots. The time slots are divided into two groups called Contention Access Period (CAP), in which the slotted CSMA/CA protocol is used for medium access, and Guaranteed Time Slots (GTS) used for contention free channel access. On the inactive part, the corresponding Zigbee device can go into sleep mode to save energy. The timing of the superframe is governed by two parameters including the Beacon Order (BO) and the Superframe Order (SO). However, the waiting time for the next active superframe and the increased complexity and overhead of indirect communication can affect the performance of time-sensitive data

transmissions, especially in the case of Pilot protection schemes for a SG application.

A non-beacon enabled Zigbee link adopts the traditional multiple access systems used in simple peer and near-peer networks, using standard ALOHA CSMA-CA communications and with positive acknowledgment for successfully received packets [151]. A peer-to-peer network allows multi-hop message routing with ad hoc, self-organizing and self-healing properties. For example, in a cluster tree peer-to-peer network, where a Zigbee device can become an FFD at different times and act as a coordinator by synchronizing with other devices in the network. However, a contention regulation mechanism is required to handle collisions. Whenever a device wants to send packets to a coordinator in a non-beacon enabled mode, it sends the data frame using un-slotted CSMA/CA. After successful reception of the packet, the coordinator replies with an acknowledgment frame.

Similarly, when a coordinator wants to send a data packet to the receiving device in a non-beacon enabled mode then the coordinator stores the packet for the particular device to make contact and request the data. The request could be initiated via transmitting a MAC command request using un-slotted CSMA-CA based on the application defined rate. Upon receiving the request, the coordinator acknowledges the successful reception of the data request by transmitting an acknowledgment frame. In the case of pending data, the coordinator sends the packet using un-slotted CSMA-CA to the device. Otherwise, when no data frame is pending the coordinator replies with an acknowledgment or with a data frame of zero payloads. Upon successful reception of the data frame, the receiving device may send an acknowledgment. Figure 2.10 summarizes the sequences described.

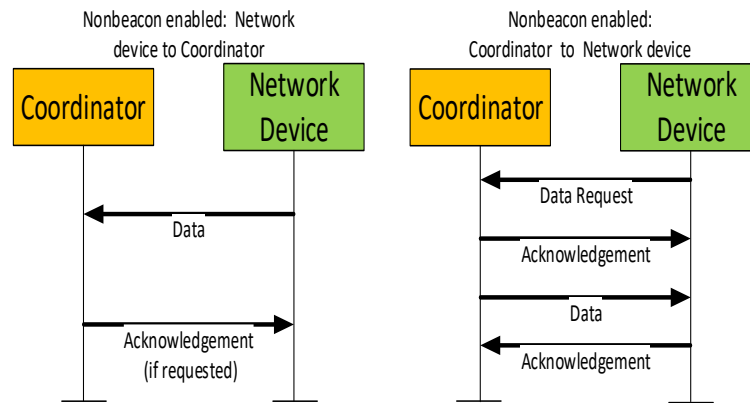


Figure 2.10 Conversation between Zigbee coordinator and network device in a non-beacon enabled mode

The 2006 IEEE 802.15.4 Zigbee revision specifies that the maximum application payload for a Zigbee frame can reach up to 101 bytes where the total frame size for the physical services can be up to total 133 bytes [151]. As mentioned earlier in a non-beacon enabled mode devices use CSMA/CA to gain access to the medium. To avoid collision, each Zigbee node first examines the channel, and if the channel is busy it waits for a randomly chosen backoff period before transmitting data. Here, the time duration is randomly specified by $[0-2^{BE}-1]$ where BE represents the backoff exponent, and the default values for the Zigbee standard is set from 3 to 5.

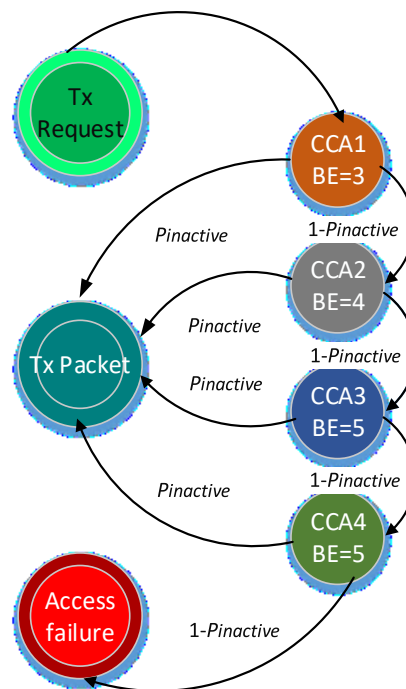


Figure 2.11 CSMA-CA packet transmission process based a Markov chain theory

Figure 2.11 shows the traversing Markov chain from the Tx Request starts state to the Access Failure final state yields the probability of a channel access failure. If the activity level is high, the likelihood of access failure increases. The following equation determines the probability of access failure.

$$P_{access_failure} = (1 - P_{inactive})^{Max_BE} \quad (2.1)$$

Where, $P_{inactive}$ is the probability of the inactivity. The maximum number a node can select a backoff period is limited to 4 times after which Access Failure is considered and transmission is canceled. If the access is granted the total end-to-end transmission delay is calculated by the following equation

$$D_{E2E} = T_{CSMA/CA} + D_{Tx} + D_{ACK_turnaround} + LIFS \quad (2.2)$$

Where, $D_{END\ TO\ END}$ is the end-to-end delay, $T_{CSMA/CA}$ is the time duration needed for channel access via CSMA/CA, D_{Tx} is the packet transmission time, $D_{ACK_turnaround}$ time to switch RF transceiver from receive to transmit mode, D_{TxACK} is the acknowledgement packet transmission time and $LIFS$ is the Interframe Spacing Time [151].

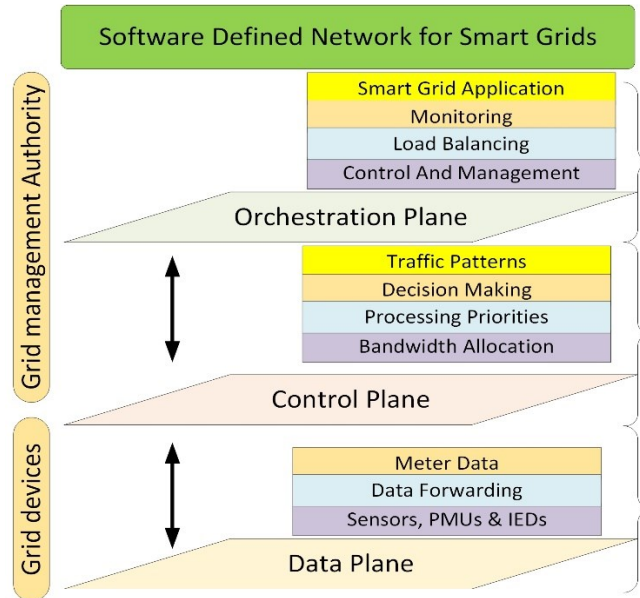


Figure 2.12 Logical architecture of SGs using an SDN paradigm

In the case of an SG NAN environment, the smart meters would be equipped with RFDs, and the network can be configured with different topologies depending on the SG application. SDN based SGs

aim to eliminate the existing challenges in the SG communication network. Grid equipment like sensors, IEDs, and PMUs transfer information over the data plane of the SDN based SG. The network devices are scattered among different domains of the power system. Grid information such as voltage, current, consumption data, and temperature are forwarded to the specific destination according to decision information supplied via the control plane. Figure 2.12 stretches our understanding on the logical architecture of SGs using the SDN paradigm. The orchestration plane handles the monitoring, control and management capabilities. From this plane, the grid authority can define, install, operate and manage new SG network services and applications. Based on the application set specified by the orchestration plane, the control plane handles the data plane. The control plane configures the data rate, allocates bandwidth for each application, sets the priority based on delay sensitivity, creates and maintains the flow table and deploys flow information switches. As the scope of this chapter is limited to analyze the network configuration of an SDN based NAN, the study mainly focused on the customer premises of the power grid.

Development of an SDN based NAN will depend on a vast number of sensors deployed via complex networks into the customer premises of the SG. To enable increased SG traffic generated from AMI applications, the network should be scalable, efficient and easily manageable. Most of the available underlying SG communications capability is hardware-centric and purposefully designed for a particular set of applications. OpenFlow protocol is the functional open standard acknowledged by the researcher community working on SDN centralized control software and distributed control software [152]. OpenFlow provides the flexibility to develop programmable control plane and to design test facility to deploy centralized control mechanism in large networks. Usually, the communication devices in an SDN network serves different functionalities in control plane and data plane. The control plane has the global observational and programming capability over the underlying network. On the other hand, the physical devices in the data plane hold the ability to forward traffic based on the configuration deployed by the centralized controller. Exploiting the unique property of SDN could

bring benefits to any conventional WSN based NAN as it can handle increasing number of M2M devices in the customer premises of SG. The proposed communication framework presented in this thesis can be used to implement highly manageable and controllable NAN. Moreover, the communication model would allow flexible deployment of innovative SG applications. [153] focused on developing an SDN based routing protocol for AMI applications in the wireless environment. However, none of the existing frameworks, either OpenFlow based or application centric, did not focus on modeling a complete SDN based SG NAN using wireless sensor network.

The greatest challenge of NANs is the limited flexibility to install and update new applications. Physical intervention in network device configuration increases physical and financial costs. With a SDN based NAN controller, network devices at the NAN can be programmed remotely, and new network services and applications can be configured without intervening with the physical sensor devices or smart meters. Also, with the retrieved control and monitoring data set new AMI applications can be modeled. Figure 2.13 presents a conceptual network architecture of a SDN based NAN. In this case the smart meters act as the end devices that generate the sensor data. The distributed NAN controllers (controller 1 and 2 in Figure 2.13) are coordinated via a single NAN controller which is further connected to a DAP. Sensor data is aggregated via the distributed controllers. A DAP is connected to each distributed controller. The aggregated data is processed through the controller and based on the application definition the controller generates the flow information to send the data to the MDMS. As the data layer and control layers are separated the proposed SDN based NAN, the MDMS can deploy SG applications by pushing the application onto the NAN controller. Based on the application, the NAN controller can send specific instructions to distributed controllers.

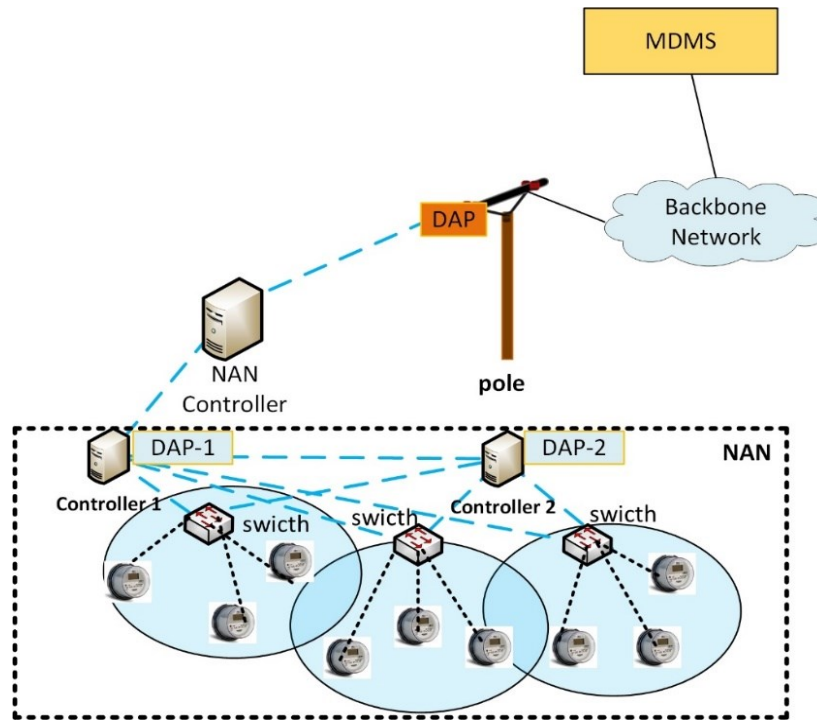


Figure 2.13 Conceptual network architecture of SDN based NAN

According to the IEEE 802.15.4g task group (TG4g), [154] the widely accepted topology for sensor nodes in an SG environment is a mesh configuration. Traffic models typically follow the TG4g specifications for supporting a large number of network devices with minimum infrastructure. SDN traffic modeling in the NAN domain is dependent on the characteristic of the AMI applications. The most common AMI applications are DR, Micro-grid management, AMR, and DERs. An AMR application collects periodic meter readings from the smart meters and sends the data to the MDMS. The meter reading data contains various power grid performance details including connectivity information and meter health status. The AMR data also can be generated at usual grid events. For example, in the case of a blackout event in a suburb, all of the smart meters will send the last gasp message to the control center. However, there are two critical aspects of this event. First, smart meters run on electrical power and will have to rely on the capacitive charge after the blackout event occurs to transmit the last gasp message. There will be a very strict delay boundary depending on the capacitor characteristics. Second, a sudden burst of data sent via a large number of smart meters will increase the collision rate and may end up causing congestion resulting in a temporary network failure. Thus, a

SDN based NAN should be robust enough to accommodate major SG applications following the delay specifications.

2.8.2. Traffic model

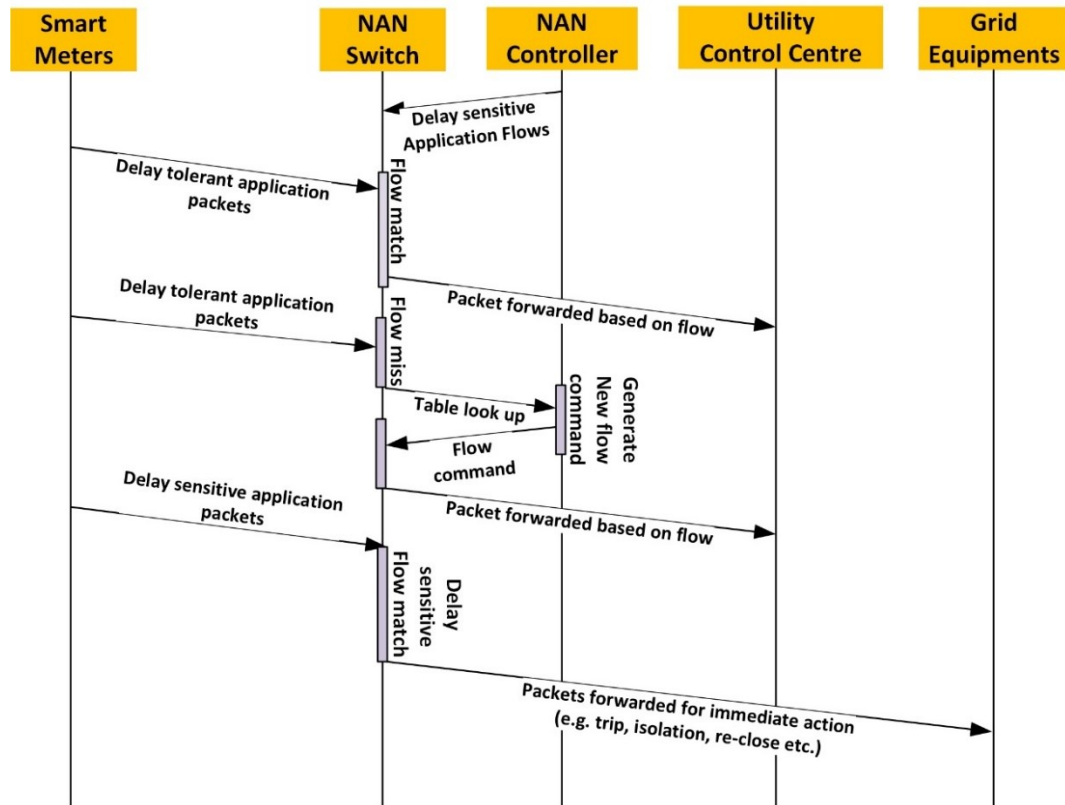


Figure 2.14 Traffic dissemination model

Figure 2.14 shows the traffic dissemination model of the SDN based NAN. The operational devices of the SDN network can be classified in five categories. These are Smart Meters, NAN switches, NAN controller, Controller at Utility center and grid equipment such as circuit breakers, grid relays or switches. Measurements from a smart meter installed at a NAN can be considered to be raw data and based on the information several SG applications can be modeled. Any newly developed application can be deployed from the SDN controller, and in this case, the NAN controller is responsible for the deployed SG application. Delay sensitive applications require guaranteed packet delivery to the destination within a strict delay boundary. Whereas, in the case of a delay tolerant application, the main objective is limited reliable and successful message transmission. The time constraint is much more flexible for delay tolerant packets.

Most of the common delay tolerant applications running on the NAN domain would be predefined by the NAN controller. In other words, the NAN switches will have predefined flow tables to forward the common delay tolerant applications. If a delay tolerant application packet is received at the switch it attempts to find instructions for how to handle the flow in the flow table; then the switch directly forwards the packets to the destination if permitted. However, for delay tolerant packets with no initial flow entry, the switch sends a request packet to the controller to get additional flow information for the new packet type. Upon receiving the new flow command from the controller, the NAN switch forwards the packet. It is interesting to notice that to get a new flow command additional flow setup time is needed. So, if there is any unknown application deployed at any instance, the total end-to-end packet forwarding delay will be increased due to the flow setup process. On the other hand, delay sensitive applications are stochastic in manner and mostly event based. Also, these application packets need to be delivered within a specific time constraint. Thus, it's inevitable to have predefined flows for such applications. If a delay sensitive packet is received at the switch, the NAN switch classifies the particular packet as a top priority message and forwards it to the destination. In most circumstances, a delay sensitive packet will be forwarded to the grid equipment or to control center for immediate action.

2.9. Potential SDN based SG application models

To illustrate the ability of the SDN based SG end to end architecture and to address various SG network services and applications, several novel usage scenarios are outlined in this section.

2.9.1. Advanced Metering Infrastructure

AMI refers to a group of smart energy meters that use two-way communication to send meter readings and receive control signals in real-time [155]. AMI smart meters remove the need to send staff to take meter readings at premises and permit measurements to be taken more frequently, which facilitates early satisfaction of changes to DR and early tampering detection leading to fraud reduction. DR enables the utility operator to optimally balance power generation and consumption either by offering

dynamic pricing or by implementing various load control programs [156]. The SDN paradigm can provide an integrated AMI solution as shown in Figure 2.15.

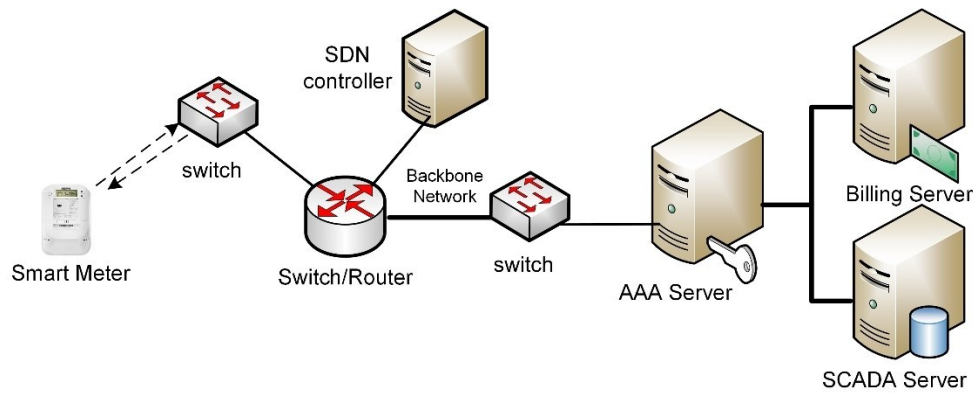


Figure 2.15 Integrated Advanced Metering Infrastructure using wireless technology

As shown in Figure 2.15, an SDN enabled AMI smart meter is connected to the switch via a wireless link. The smart meter sends meter readings to the Billing Server over the uplink and receives control signals from the Supervisory Control & Data Acquisition (SCADA) Server over the downlink from the network control center. The switch adjacent to the smart meter filters the applications related information from the data packets before sending them to the AAA server.

The AAA server authenticates the meter and authorizes energy flow for each of the connected loads. The Billing Server provides real-time pricing and energy consumption information on the meter's display so that the customers can regulate their own consumption. Also, the SCADA Server executes load-control programs by sending control signals to the target appliance(s) via the smart meter.

2.9.2. Substation Automation

Substation automation refers to the monitoring, control, and communication functions on substation and feeder equipment such as supervisory control of circuit breakers, load tap changers (LTCs), regulators, reclosers, sectionalizers, switches and capacitor banks. The utility operators are expected to use standardized communication protocols like IEC61850 to support various DA functions [157].

The IEC61850 protocol is based on interoperable IEDs that interact with each other, either within a

substation (e.g. protection signals to circuit breakers) or on feeders (e.g. automated reclosers and switches along a feeder responding to isolate a fault). The IEC61850 protocol runs over a commercial communication network including Ethernet. A consolidated SDN network can connect all the substations with each other and with the control center and thereby extend the domain of the automation functions from a single substation to the whole transmission and distribution network. A SDN based heterogeneous network (HetNet) could connect the substations using available wireline infrastructure such as DSL, fiber, and coaxial cables in conjunction with newly deployed wireless networks [158]. In this case, the SDN controller will provide authentication, security, and QoS to substation IEDs irrespective of the access network technology.

In the case of wireline connectivity, the interworking between the communication network and the IEC61850 substation bus can be performed by an Ethernet switch that aggregates the data from substation IEDs and transfers it to the controller, as shown in Figure 2.16.

The SDN controller provides a transparent IP connectivity between the substation IEDs and the SCADA servers of the control center. The AAA server provides authentication services to the IEDs, and the policy server enforces QoS profiles such that the control signals get higher priority than the statistical and monitoring information. The servers in the utility control center can also provide a single control and communication platform to the SG via the SDN controller. The convergence of control and communication entities can further reduce the latency of delay sensitive control signals and thus provide faster response to the fault conditions.

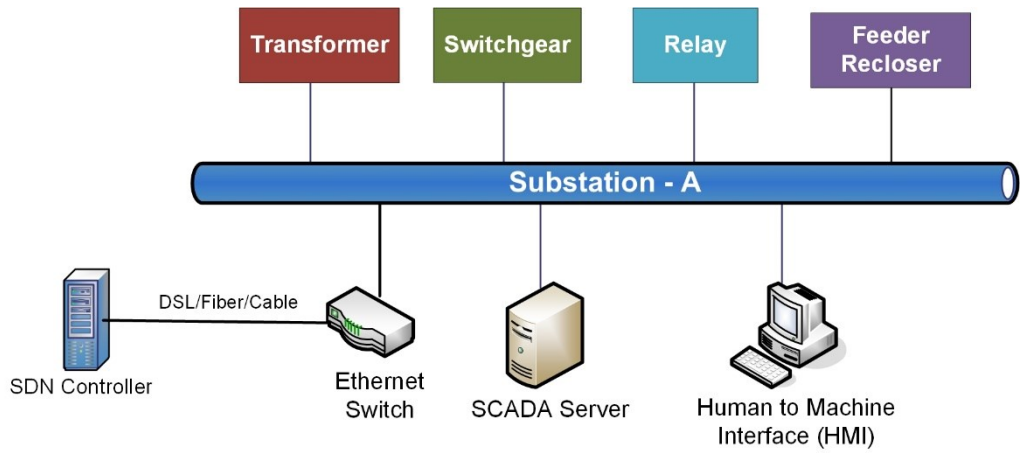


Figure 2.16 Substation Connectivity using SDN Wireline Access Network Interworking

2.9.3. Distributed Energy Resources

DER are small sources of power generation and storage that is often connected to the distribution system. To facilitate the large-scale integration of DERs into SGs requires a robust communication network to connect the DER sites and perform a variety of active distribution management functions [159].

Since the DERs are typically located within the various business, residential and industrial premises over a large geographic area the Long Term Evaluation – Advanced (LTE-A) Femtocell provides a suitable wireless communications system to connect the locally dispersed sites with sufficient capacity and coverage. LTE-A Femtocells are specialized low-cost and low-power home base stations that connect user terminals to the LTE-A core network using a locally available broadband connection [160]. Since Femtocells are placed in the customer premises and uses third party broadband connections, the cost of network deployment is reduced to a large extent. Figure 2.17 illustrates the remote DER connectivity with LTE-A Femtocells.

The Femtocells should be configured in Private Access Mode so that only pre-configured users have access to the network and ensure more network security [161]. Also, the extensive user authentication and data encryption techniques of the LTE-A network should be used in order reduce the security threats associated with using a third-party network for backbone connectivity.

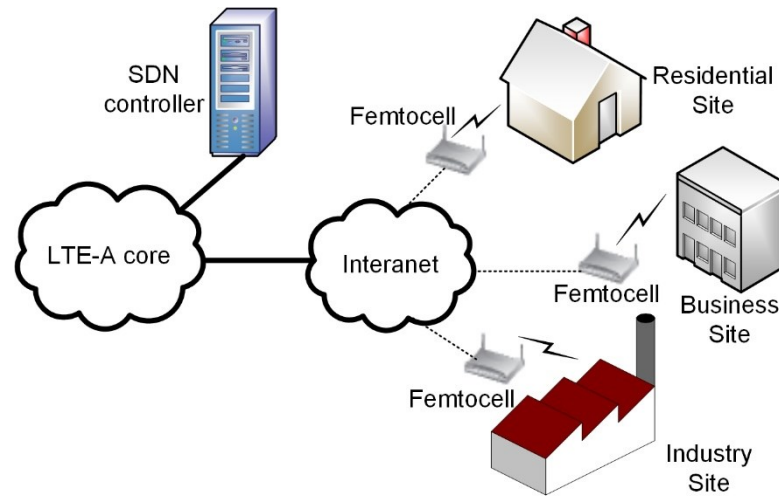


Figure 2.17 Connectivity of DERs using LTE-A Femtocells

2.9.4. Wide Area Measurement System

WAMS refers to an advanced sensing and measurement system that continuously monitors power grid performance and provides operators with high-quality data and analysis tools [157]. In a WAMS, the system state and power quality information are obtained from the state measurement modules based on the PMU. The results from the PMUs are then combined with a CCN to display the system stability measures in real-time and an SCADA system for remote monitoring and control. PMUs utilize the GPS to provide a time-stamp for each phasor measurement [162].

As PMUs are scattered throughout the power system, WSNs are an appropriate option to collect real-time information. Data from the WSNs can be conveyed to the CCN via LTE-A base stations (eNodeBs) connected in a mesh topology. LTE-A serves as a wireless access network technology to integrate the sensor sub-networks and for connecting the WSN to the CCN.

Also, the Mobile Management Entity (MME) can act as the PDC for the PMUs and provide a secondary clock reference along with the GPS. One concern for this WSN-LTE-A hybrid network is that the security of the overall system depends on the security of each network component. Therefore, the AAA server in the LTE core should periodically authenticate all the WSN entities along with the end PMU devices. Figure 2.18 shows the connectivity of PMUs using remote WSN and LTE-A.

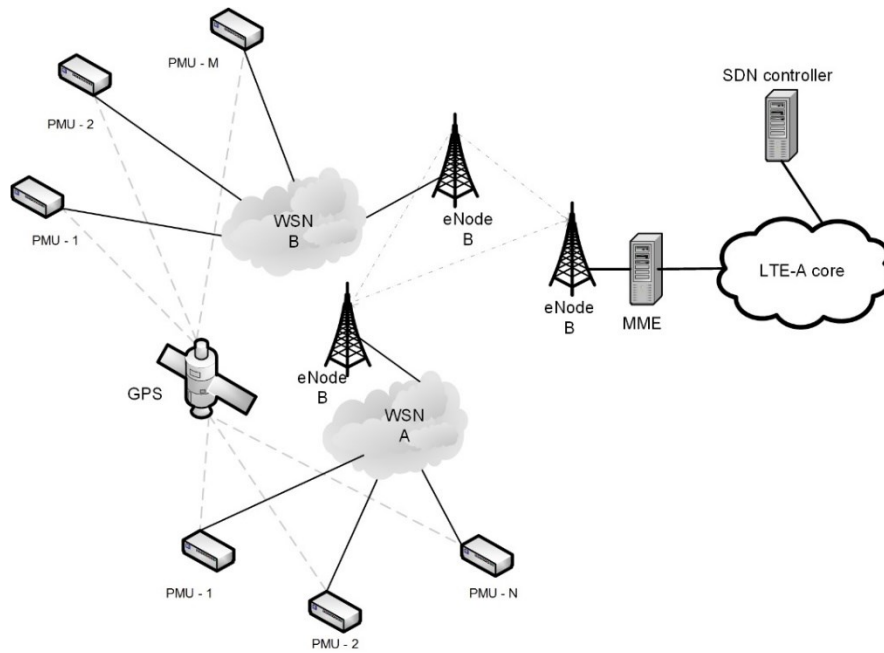


Figure 2.18 Wide Area Measurement using LTE-A Connected Wireless Sensor Networks

2.9.5. Plug-in Electric Vehicle Roaming

Transformation of conventional power grids into SGs promises revolutionary changes through extensive usage of renewable energy resources which will enable ‘green energy’ generation. Oil price increases and the shift towards green technologies are motivating the transportation industry to introduce electric and hybrid vehicles. The oil price touched a peak value of \$147 per barrel in 2008 [163], and according to the Electric Power Research Institute (EPRI), 35% of the total vehicles in the USA will be PEVs by 2020 [164]. As a demand source, new PEVs or Hybrid PEVs (HPEVs) draw a substantial electrical load from the grid to keep them operating. As a supply source, PEVs could act as a mobile power storage device which may store energy from a renewable resource and provide a backup supply in times of need.

PEVs often remain parked for long periods, recharging for some of this time and PEVs typically travel over similar routes daily. V2G power transmission may reduce the grid’s load during peak demand or at times when the grid is under stress due to unexpected events. According to [163] PEVs, battery storage varies between 1 to 30 kWh, and the output ranges from 0.2-6 KW if the battery requires 5 hours to charge or discharge. Thus, with V2G there is an opportunity for real-time DR programs and

ancillary services like peak power and spinning reserves to be implemented [164][165]. However, to enable these services with a large number of PEVs, additional equipment such as aggregators at different SG domains are required. [166] argues that a Mid-Atlantic US (PJM) power grid operator can aggregate up to 1MW of power from a fleet of 100 vehicles with 15KW V2G

PEVs are regular hybrid vehicles that have a large high-capacity battery bank. The vehicles draw power from the grid during off peak hours to charge the batteries and provide power back to the grid during peak hours. Thus, they can play a vital role in balancing power generation and consumption [167]. Since the PEVs are highly mobile, integrating them into the SG can be a major challenge.

The advanced roaming model of an LTE-A network architecture can enable utility operators to allow flexible charging and de-charging of PEVs anytime, anywhere and in any utility network using an onboard smart meter. Figure 2.19 shows the roaming scenario of a PEV with an onboard LTE-A smart meter.

The charging station is located within the visited LTE-A network, and the smart meter in the PEV authenticates itself and sends metering information to the AAA and Billing Servers of its home network. Communication between the home and visited networks is carried out using the AAA proxy servers located at the edge of each network. The visited network provides network access to the PEV, and the inter-operator billing is settled later using a potentially standardized roaming agreement.

PEV integration with SGs is an important challenge that has evolved as PEV have shifted from a research topic to reality. Exemplary conceptual frameworks on the topic can be found in [168][169]. A smart model of PEVs charging in a WAN is presented in [170] where WiMAX is selected as the communications technology. However, the work mainly focused on the communication network model development to accommodate a maximum number of vehicles. Other works related to G2V applications in SGs focus on optimization techniques for smart energy aggregation [168] [171] [172]. [170] adopted a step charging mechanism with an adjustable optimized period to maximize battery

charging accuracy.

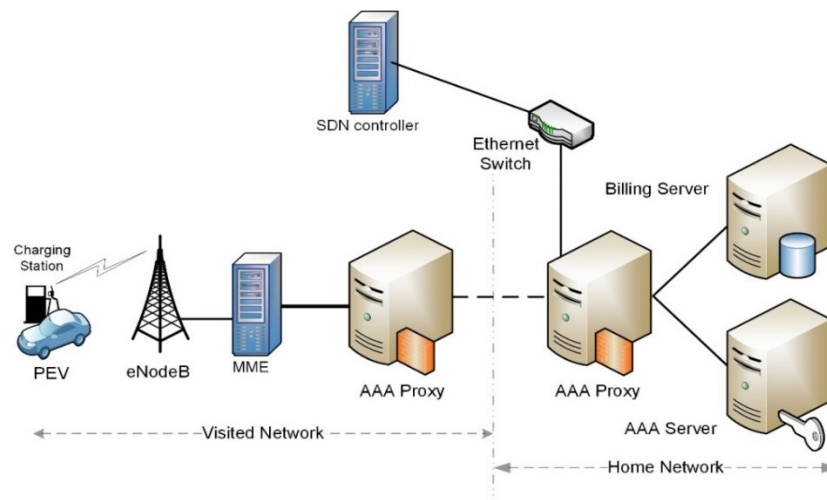


Figure 2.19 Roaming of EVs using SDN and LTE-A

However, to develop a G2V based PEV charging application, it is essential to have knowledge of vehicle energy state parameters such as battery status and charging rates. Smart aggregation and synchronization of energy state parameters received from each PEV are very important for an optimal outcome. Hence, a robust communication network architecture is an important requirement and should have adequate capacity for the large number of energy state reports generated by the PEVs. An under-designed network architecture would be overwhelmed by a sudden burst of network access attempts and will suffer from excessive network delay and congestion.

2.10. Summary

The chapter presents a comprehensive survey of the SG architecture, potential applications, and standardization effort by reviewing recent literature, reference models and standards. As SGs are an enormously broad and diverse network of electronic devices, there is a significant challenge to model the communication network requirements. A summary of the standardization effort is provided for future investigators, professionals, and researchers. The chapter initially focuses on the SG communication network architecture, network topologies, and functions. The standardization initiative taken by different organizations, nations and regions are then described. Potential SG applications and communication requirements are also presented. The aim is to provide information about how to build

a smart, reliable, secure power grid and to identify the requirements and challenges associated in the development of SG applications. Further, the chapter provided a high-level study of an end to end SDN based SG network architecture that highlights the further application to key SG applications. An end to end SDN based NAN can be used to provide an integrated AMI network that can perform various DR programs effectively and efficiently. It can connect different substations using its flexible interworking capability with wired and wireless technologies and thus leverage the substation automation function domain from a single substation within the power system. Also, it can connect the dispersed DERs using LTE-A Femtocells and PMUs using WSN via its backbone network. It can also facilitate PEV roaming using its advanced roaming capabilities. This list of scenarios is not exhaustive and it is expected that several more scenarios will also emerge. SDN could be a key enabler for future 5G networks and the Internet of Things (IoT). Aligned with this shift to introduce flexibility and programmability into networks, the future of SGs could significantly benefit through the smart utilization of the SDN paradigm.

CHAPTER 3. Application based traffic modelling and performance analysis

3.1. Overview

This chapter includes contributions that address research question 1. Efficient traffic models are presented along with end-to-end network architectures to support major SG applications. Appropriate wireless technologies have been selected to support the SG application traffic models for the corresponding SG domains. The proposed system models are further supported by novel mathematical frameworks, algorithm and an appropriate simulation model. A Zigbee based pilot protection scheme is developed that would operate within the distribution grid of the SG. The study represents the potential of WSNs to support pilot protection application while satisfying the strict delay boundary. A test bed setup is also presented to support the simulation models developed in Castalia. The second application model presented in this chapter demonstrates HetNet based communication network to support V2G power management. V2G would be a major SG application while electricity would be the only source of power for vehicles all around the world. A prediction algorithm is proposed to estimate the required power that needs to be supplied to the grid during the peak hours. Further, an OPNET based simulation is developed to analyze the performance of the proposed model and validate claims. The third model presented in this chapter includes a novel WiMAX ranging scheme that can support large number of M2M applications in a SG. The claims are further supported by extensive simulation based result analysis. Analysis of different application-centric SG traffic modeling is carried out using appropriate simulation tool (such as Castalia [173] and OPNET modeler [174]) by developing discrete event simulation models. OPNET Modeler provides a comprehensive development platform for modeling distributed systems using finite state machines (FSM). On the other hand, a Castalia simulation environment follows the modular structure of OMNET++ [175]. A Castalia node consists of five modules including Sensor Manager, Application, Communications, Resource Manager and Mobility Manager. The scalable module structure provides the flexibility to develop and test new distributed algorithms and

protocols. These, simulation models generate large datasets of expected performance measurements such as an end-to-end delay, packet loss and network throughput.

3.2. A Novel Zigbee Based Pilot Protection scheme

A novel pilot protection scheme was developed through a Zigbee wireless mesh network which maintains the strict delay requirement of the pilot signals. To support pilot protection schemes in the smart distribution grid an IEEE 802.15.4 Zigbee based wide area wireless network is investigated. For peer-to-peer communication among the relays, the IEC 61850-90-5 based GOOSE protocol is considered. The approach presented is supported by simulation results. Furthermore, a test bed experiment based on the CC2350 radio chip (Zigbee protocol stack) [176] was used to verify the simulation results.

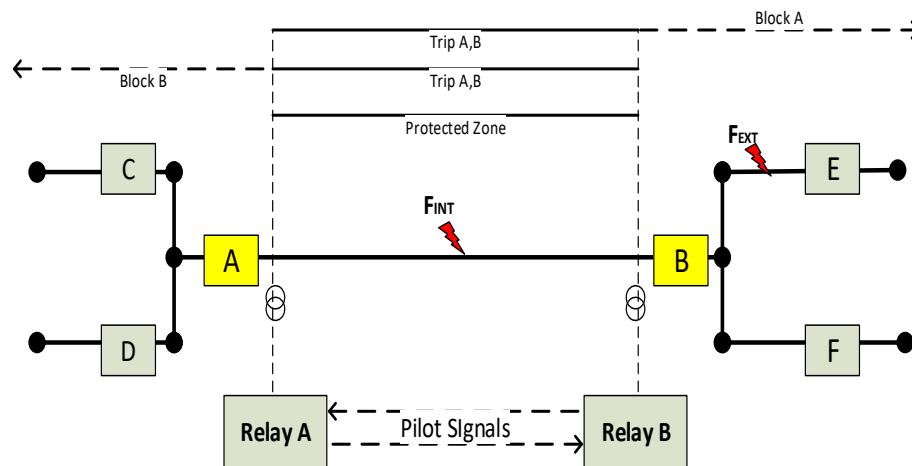


Figure 3.1 DCB and/or POTT pilot protection scheme

A pilot relay calculates the impedance at a terminal to identify an internal or external fault. The fault will be internal if its power is detected to be flowing inward at all line terminals. Otherwise, if the fault direction is out from the line at one terminal and into the line at another terminal, the fault is considered to be external. A relay needs to trip for an internal fault and block tripping for an external fault. Under a pilot protection scheme based on DCB, a pilot block signal is exchanged between the peer relays to block tripping in case of a reverse fault and to trip in case of an internal fault. Similarly, the POTT scheme uses a permissive transfer trip signal if the fault is in front of the relay. Figure 3.1 shows a

schematic diagram of the basic mechanism of exchanging pilot signals where a trip takes place in both terminal A and B; only if the relay detects a fault F_{INT} in between these two terminals and a permissive trip signal is received where no block signal is received from A and B. On the other hand, if a fault F_{EXT} is detected outside of B, a pilot block signal is sent to block A from tripping. For more information on the pilot protection schemes refer to [131]. Please note that, network communication requirement is specified in Section 2.7.1. The fundamental challenge associated with pilot protection scheme is to transfer the pilot messages within the strict delay boundary.

A Castalia based simulation model was developed to evaluate the pilot protection scheme over a ZigBee network. The system parameters and their settings used in this experiment are summarized in Table 3.1. In this experiment the CC2530 radio chip specifications have been used and thus corresponding parameters have also been reflected in Table 3.1. The CC2530 has been introduced by the Texas Instrument (TI) as a high-performance Radio Frequency transceiver and supports IEEE802.15.4 Zigbee protocol system on a chip in the 2.4 GHz band. The CC2530 is a competitive ZigBee solution with a combined Texas Instrument's/Chipcon's ZigBee protocol stack [176].

It is assumed that each protected zone consists of two protective relays. Protection signals are exchanged between these protective relays via two Zigbee end devices/communication relay nodes. Thus, in total, four nodes are used in each protection zone. A protected zone extends to about 1 Km. The final simulation network was overlaid with the consideration that there are two protected zones per Km². In total, 198 protective relays are deployed in a 10.5 km × 9.9 km rectangular area. Simulations were run for one hour with the consideration that each protection zone experienced a single fault in one hour producing 396 pilot signals. The fault generations are considered to be mutually non-exclusive i.e. faults were generated randomly during the simulation hour with the possibility of multiple faults could occur simultaneously.

Table 3.1 Simulation Parameters of the pilot protection scheme

<i>Parameter</i>	<i>Setting</i>
Transmission Power	4.5 dBm (<i>SH</i>)
Data Rate	250 Kbps
Modulation Type	PSK
Bits Per Symbol	5
Bandwidth	5 MHz
Noise Bandwidth	-100 MHz
Noise Floor, Sensitivity	-100 dBm, -95 dBm
MAC Protocol	Std MAC 802.15.4
Background Traffic (packet per second)	100-400 pps
Number of Protected Zone	99
Coverage Area	10.5 Km \times 9.9 Km (103.95 Km ²)
Number of Zigbee Nodes	396
Number of Protective Relays	198

A real-life SG is also responsible for other traffic such as delay tolerant messages and M2M traffic for applications in the grid including smart metering, DR, periodic sensor reports and so on. This traffic was emulated in this experiment by producing variable background traffic that is varied between 100 to 400 pps (packets/sec) with a step of 50 pps. The following two metrics were used for performance analysis:

- **Success Rate:** The percentage of total pilot messages that were received successfully within the threshold time.
- **Latency:** Time is taken to deliver pilot messages successfully from a protection relay to its peer relay.

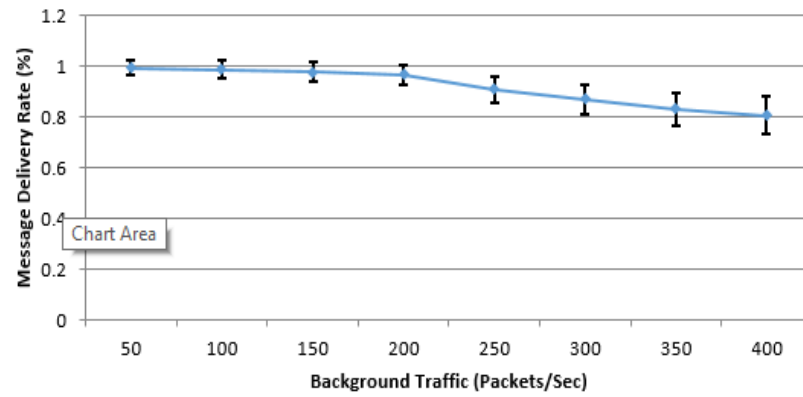


Figure 3.2 Message Success Rate

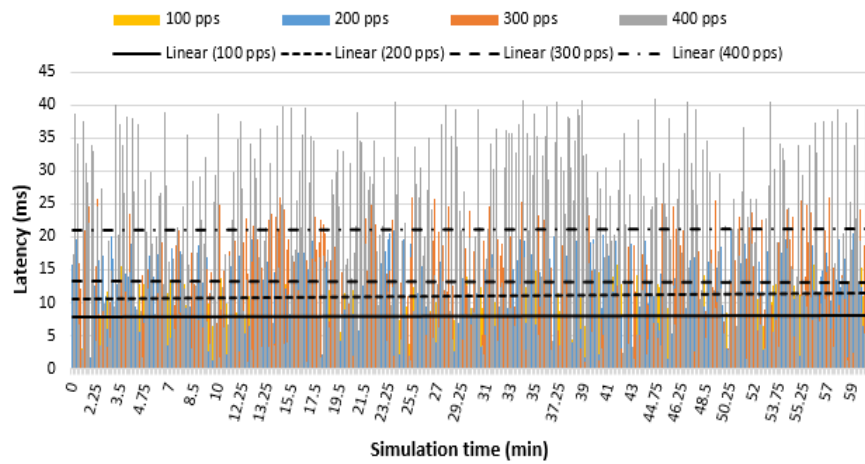


Figure 3.3 Latency of Pilot Messages under different traffic load

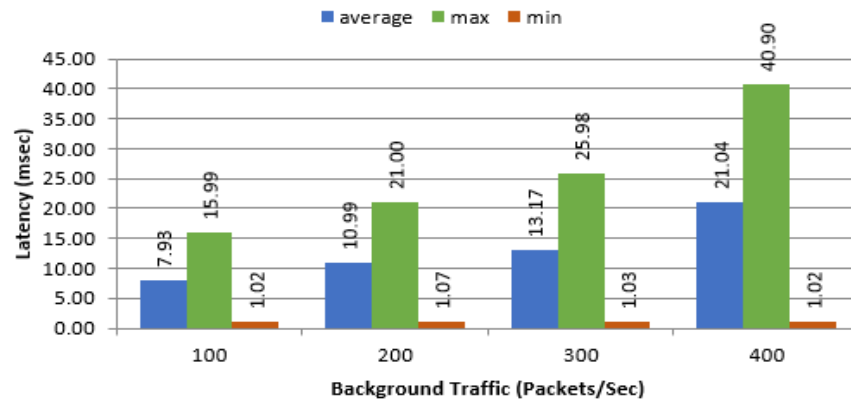


Figure 3.4 Aggregated Latency in Four Different Cases

Figure 3.2 shows the percentage of pilot messages that have been transmitted successfully as a function of background traffic per second. In this scenario, the delivery rate decreases with the increase in background traffic. However, from Figure 3.2, it is seen that the percentage of messages delivered was almost steady until the background traffic was less than 200 pps and then it begins to fall. In Figure

3.3, latency increases as the background traffic grew. The solid lines in Figure 3.3 reflect the corresponding linear trendline. The trendline demonstrates that the average latency of the successful pilot message remains within the strict 30 ms boundary duration. However, the average, maximum and minimum latency for each case is shown in Figure 3.4 where it is clear that in the case of high background traffic, such as 400pps, this pilot protection scheme fails to meet the latency requirement.

3.2.1. Demand Based Priority Queuing

Results shown in the previous section demonstrate the vulnerability of the conventional Zigbee based pilot protection scheme. To overcome the limitation, a Demand Based Priority Queuing (DBPQ) technique is proposed and implemented in the application layer. In general, all application layer packets are pushed into a queue referred to as *TxBuffer*. Packets in *TxBuffer* are transmitted in their next corresponding transmission slot in a FIFO fashion. In DBPQ, each pilot protection packet has been associated with high priority while all others are assigned low priority. If an incoming packet to the *TxBuffer* is of pilot protection kind, then a two level (priority, order) sorting algorithm is applied on *TxBuffer* after inserting the packet, as shown in Algorithm 3.1.

Algorithm 3.1 buffering(application_packet pkt), implemented at each node. Packets are associated with priority and order

1. switch (pkt->getApplicationPacketKind())
 - a. case **PILOT_PROTECTION_MSG**
 - i. push the *pkt* into the *TxBuffer*
 - ii. sort *TxBuffer* based on priority and order.
 - b. case **BACKGROUND_TRAFFIC**
 - i. push *pkt* into *TxBuffer*
 2. return
-

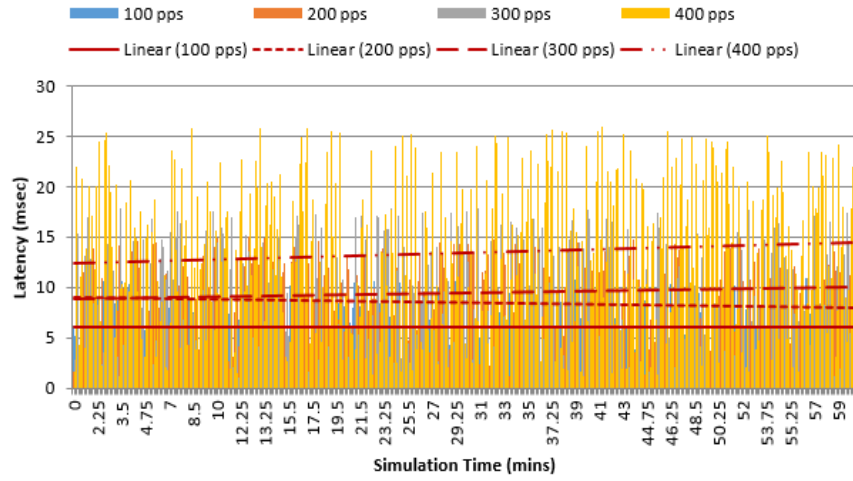


Figure 3.5 Latency of Pilot Message after Applying DBPQ

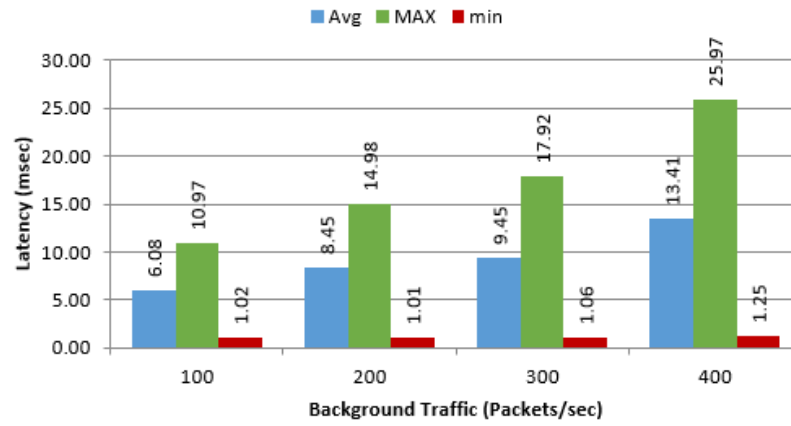


Figure 3.6 Aggregated Latency in Four Different Cases (DBPQ)

Figure 3.5 shows the end-to-end delay and latency observed after DBPQ was applied. With the proposed DBPQ technique significant improvement is achieved while reducing the end-to-end delay and latency in case of the high background traffic scenario. Figure 3.6 shows the latency statistics using the DBPQ algorithm. The maximum value reached 25.97ms with 400 pps background traffic which remains below the required threshold of the pilot protection scheme.

3.2.2. Test Bed Experiments and Analysis

To analyze the feasibility of the proposed DBCA mechanism, a test bed experiment was configured with the CC2530 radio chip (Zigbee protocol stack). Two Zigbee devices were configured and installed 300m apart from each other (shown in Figure 3.7) in the RMIT University city campus.

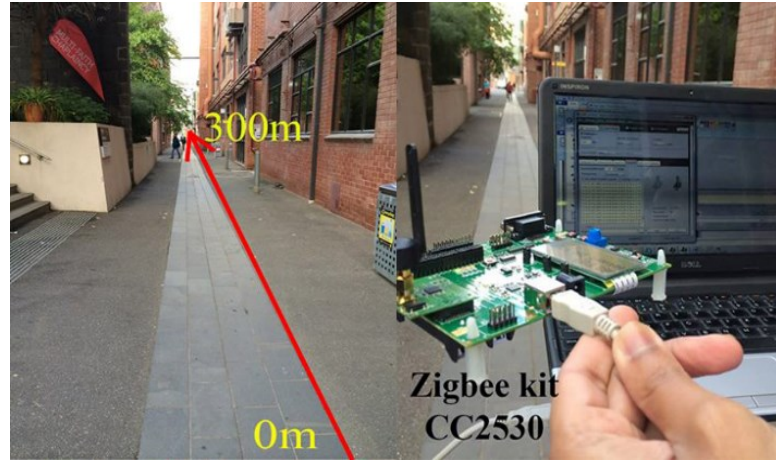


Figure 3.7 Test Bed Experiments

The feasibility of the proposed scheme was tested by successfully delivering all of the pilot signals between the peer end-device/protective relays with background traffic of 400pps. Five sets of experiments were conducted, and the average latency remained within the strict boundary requirement of the SG pilot protection application. The Line of Sight (LoS) between the devices was considered in the simulation, it was also maintained during the test bed experiments. The latency and average receiver sensitivity statistics are summarized in Table 3.2. To keep the scope of the research limited, the effect of packet loss was not considered while conducting the test bed experiment. Also, no retransmission was considered as it's very difficult to incorporate a retransmission mechanism for a delay intolerant application such as the pilot protection scheme.

Table 3.2 Experimental Results

<i>Experiment ID</i>	<i>Maximum latency (ms)</i>	<i>Receiver Sensitivity</i>
1	18.7	-82.1dBm
2	17.4	-75.8dBm
3	17.6	-72.7dBm
4	18.2	-73.4dBm
5	18.9	-81.6dBm

3.2.3. HetNet Based V2G

In this section, a network controlled V2G load management scheme for discharging PEVs is presented which utilizes the bi-directional communication capabilities of SGs. To initiate aggregation from the fleets parked at the charging/discharging stations, a prediction algorithm is developed based on a

Linear Prediction (LP) model [177][178]. Also, a HetNet based M2M communication system is introduced to provide V2G aggregated load management for peak shaving. An energy scheduling algorithm is proposed to ensure priority and smart forecasting of large-scale PEV discharging under the proposed scheme. The performance analysis of the proposed algorithm over a WiMAX-WLAN wide-area SG communications network is presented using an OPNET simulation model.

The proposed V2G load management scheme is significantly different to research contributions found in the literature because it considers an efficient optimization technique along with a robust heterogeneous communication network. [179][180][181][182] focused on optimization techniques to balance load curves and to maximize profits via energy pricing. [179] presents a regulation algorithm for optimal charging based on unidirectional V2G. A stochastic mixed integer linear programming technique is formulated to compare coordinated and uncoordinated PEVs charging performance to mitigate the risk of the day ahead pricing of V2G services in thermal and wind power plants is presented in [183]. However, implementation of these optimization schemes requires precise early information about the energy states (e.g. charging rate, battery status) of the PEVs. In such cases, communication networks act as the key enabler for disseminating synchronous state reports to initiate the optimization periods. In this context, the network may become overwhelmed with traffic bursts resulting in network congestion with increased delay and poor optimization outcomes.

The proposed model utilizes a prediction algorithm to estimate the peak demand and then the aggregators coordinate available energy resources, PEVs, via statistical multiplexing to provide differentiated energy supply for handling peak demand. Also, the controller is required to communicate with a limited number of Access Points (AP) which reduces the overall system communications load and evenly distributes the communications load by randomizing the uplink packet transmissions from the APs. Hence, regarding communication overhead, the scheme is highly robust and scalable and can be integrated with other SG applications.

3.2.3.1. V2G load management scheme

A. Conceptual model

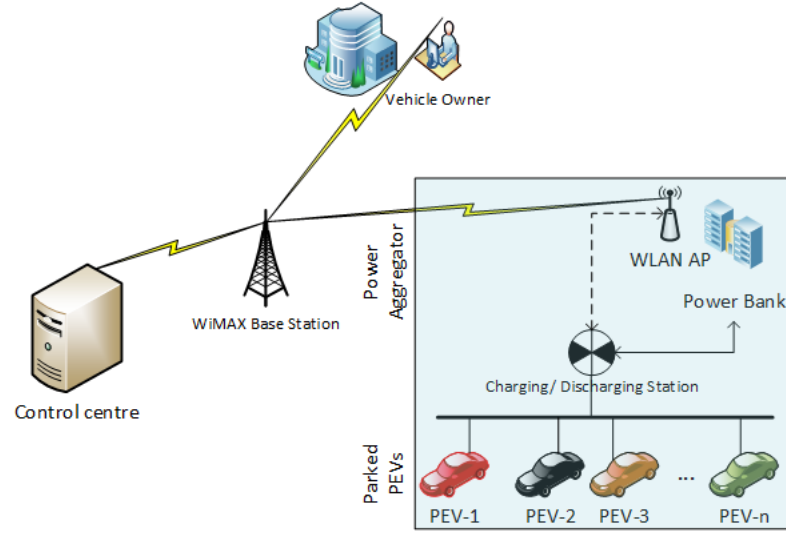


Figure 3.8 Modes of connectivity within the proposed V2G system

Figure 3.8 presents a simple illustration of the proposed HetNet based V2G model. Based on the proposed V2G model, the primary intention was to develop an SG application for peak power management. In this scenario, the PEVs act as a mini power bank and store energy while charging overnight. During the next day, excess stored energy could be returned to the grid when the vehicle is parked at parking areas equipped with charging and discharging stations. The proposed architecture consists of parking spaces equipped with charging and discharging stations, PEVs, WiMAX based stations, WLAN APs and a control center for regulating the power drawn from the parked PEVs. The discharging station has WLAN access points installed, enabling discharging facilities to act as aggregators. Energy aggregation is initiated based on a request sent by the control center. The energy is stored in the power banks installed at the charging and discharging stations. Details of a large-scale energy storage implementation can be found in [184]. The control center determines the time to initiate a request based on peak demand forecasts. The WiMAX network is used to provide link communication to the control centers. Note that, the proposed scheme also adopts a request/grant mechanism to allocate energy aggregation from the PEVs. The owners of the PEVs receive a permission request message to initiate energy discharge with the option to limit the discharge amount.

To initiate aggregation from the vehicles parked at the charging/discharging station, it was necessary to develop a peak demand prediction algorithm that would permit vehicle energy discharge to occur before the power would be needed and to provide the aggregator with the time required to aggregate available energy. Also, time must be allowed for vehicle owners to be notified that energy discharge from their vehicle is requested and for a response to be received. The prediction model for estimating peak demand is an LP model [177][178] and uses real-time load information to predict the load curve during the next day, which provides an hourly load on the grid. LP models are used in a wide variety of applications in different fields, for example, in data forecasting, speech coding, video coding, speech recognition, signal restoration, and other traffic flow models. They are often referred to as autoregressive (AR) processes in the statistical literature. In such a system, if the input and output at time t are indicated by $x(t)$ and $y(t)$, then the prediction algorithm predicts the future output $y(t)$ by using previous system inputs and outputs. At time $t = n$ the prediction of $y(n)$, denoted as $\hat{y}(n)$, is calculated by

$$\hat{y}(n) = \sum_{k=1}^p f(x) \quad (3.1)$$

$$\hat{y}(n) = a_0 + a(k)y(n-k) + \sum_{k=0}^N b(k)x(n-k) \quad (3.2)$$

Where the coefficients $a(k)$ and $b(k)$ are determined in such a way that $\hat{y}(n)$ approximates the real output of $y(n)$ as accurately as possible using an auto-correlation approach. The proposed modified LP model (MLPM) is used to best fit the OPNET HetNet network model simulation was developed for fast computation and minimum prediction error. Using the MLPM demand load information is gathered and used to calculate the weight coefficients that will be used the next day.

If the power consumption of n users at time slot t is $D(t)$, then the total power consumption will be

$$E_n = \sum_{t=1}^L D_n(t)\lambda \quad (3.3)$$

Where, L is the number of time slots over the 24 hours of a day, each with length λ .

So, if the current time is 't' and we want to estimate the demand at '(t+T)', the real-time demand information $\{D_j^k\}_{k=t-N+1}^t$, at 't' can be used to approximate the value of P_j^{t+1} at time (t+1) using

$$P_{t+1} = w_1 D_j^{t-N+1} + w_2 D_j^{t-N+2} + \dots + w_N D_j^t \quad (3.4)$$

Where, P_{t+1} is the predicted value of D_j^{t+1} and N is the number of weighting coefficients (i.e. $w_1, w_2, w_3, \dots, w_N$). Similarly, the value of D_j^{t+2} is predicted by

$$P_{t+2} = w_1 D_j^{t-N+2} + w_2 D_j^{t-N+3} + \dots + w_N P_{t+1} \quad (3.5)$$

Thus, the generalized form of the predicted demand at time (t+T) is

$$P_{t+T} = \sum_{k=1}^{T-1} P_{t+T-k} w_{N-T+2} + \sum_{k=T}^{N-T+1} D_j^{t+T-k} w_{N-k} \quad (3.6)$$

To determine the coefficient 'w', M previous data samples are used (i.e. $D_j^t, D_j^{t-1}, \dots, D_j^{t-M+1}$), where ($M > N$). Let,

$$D_m = \frac{1}{M} \sum_{k=t-M+1}^t D_j^k \quad (3.7)$$

And,

$$\bar{D}_j^i = D_j^i - D_m \quad (3.8)$$

To calculate w from the data samples, the following algorithm, which is a simple extension of the LP algorithm, is proposed. Let,

$$A \cdot W = Y \quad (3.9)$$

Where,

$$\begin{bmatrix} \bar{D}_j^{t-M+1} & \bar{D}_j^{t-M+2} & \dots & \bar{D}_j^{t-M+N} \\ \bar{D}_j^{t-M+2} & \bar{D}_j^{t-N+3} & \dots & \bar{D}_j^{t-M+N+1} \\ \vdots & \ddots & \dots & \vdots \\ \bar{D}_j^{t-M+N} & \dots & \dots & \bar{D}_j^{t-M+2N-1} \\ \bar{D}_j^{t-M+S} & \dots & \dots & \bar{D}_j^{t-1} \end{bmatrix} \begin{bmatrix} w_1 \\ \vdots \\ w_N \end{bmatrix} = \begin{bmatrix} \bar{D}_j^{t-M+N+1} \\ \bar{D}_j^{t-M+N+2} \\ \vdots \\ \bar{D}_j^{t-M+2N} \\ \bar{D}_j^t \end{bmatrix} \quad (3.10)$$

Now, let

$$\mathbf{A} = \begin{bmatrix} \bar{D}_j^{t-M+1} & \bar{D}_j^{t-M+2} & \dots & \bar{D}_j^{t-M+N} \\ \bar{D}_j^{t-M+2} & \bar{D}_j^{t-M+3} & \dots & \bar{D}_j^{t-M+N+1} \\ \vdots & \vdots & \ddots & \vdots \\ \bar{D}_j^{t-M+N} & \dots & \dots & \bar{D}_j^{t-M+2N-1} \\ \bar{D}_j^{t-M+S} & \dots & \dots & \bar{D}_j^{t-1} \end{bmatrix} \quad (3.11)$$

$$\mathbf{W} = [w_1 \ w_2 \ \dots \ w_N]^T \quad (3.12)$$

And

$$\mathbf{Y} = [\bar{D}_j^{t-M+N+1}, \bar{D}_j^{t-M+N+2}, \dots, \bar{D}_j^{t-M+2N}, \bar{D}_j^t]^T \quad (3.13)$$

Let us define,

$$\begin{cases} e_1 = |w_1 \bar{D}_j^{t-M+1} + w_2 \bar{D}_j^{t-M+2} + \dots + w_N \bar{D}_j^{t-M+N} - \bar{D}_j^{t-M+N+1}| \\ e_2 = |w_1 \bar{D}_j^{t-M+2} + w_2 \bar{D}_j^{t-M+3} + \dots + w_N \bar{D}_j^{t-M+N+1} - \bar{D}_j^{t-M+N+2}| \\ e_s = |w_1 \bar{D}_j^{t-M+N} + w_2 \bar{D}_j^{t-M+N+1} + \dots + w_N \bar{D}_j^{t-M+2N-1} - \bar{D}_j^{t-M+2N}| \end{cases} \quad (3.14)$$

Where, $|\cdot|$ indicates absolute value. Select $w_1 \dots w_N$ to minimize $e_1 \dots e_s$ using the least square solution of (3.10). The least square solution selects w_1, w_2, \dots, w_N such that $e_1^2 + e_2^2 + \dots + e_s^2$ is minimized. In mathematical form, the optimization of the least square problem can be defined as

$$\min_w ||\mathbf{A} \cdot \mathbf{W} - \mathbf{Y}||_2^2 \quad (3.15)$$

This is a convex optimization problem which can be solved using linear programming. In fact, the optimization has a compact form, and the well-known solution of this problem is found in [185], which is given by

$$\mathbf{w} = (\mathbf{A}^T \mathbf{A})^{-1} \mathbf{A}^T \mathbf{Y} \quad (3.16)$$

So, (3.6) and (3.7) become

$$\bar{P}_{t+T} = \sum_{k=1}^{T-1} \bar{P}_{t+T-k} w_{N-T+2} + \sum_{k=T}^{N-T+1} \bar{D}_j^{t+T-k} w_{N-K} \quad (3.17)$$

And,

$$P_{t+T} = \bar{P}_{t+T} + D_m \quad (3.18)$$

Now assume, at $(t+T)$ hour, the peak hours start when generation needs to satisfy the highest daily demand and generation needs to turn on additional power supply generators. In this case, the

aggregated energy from the discharged vehicles will be used to make up the gap between the present supply curve and the peak demand curve. Let us assume; the total aggregated energy δ_m^{t+T} from the APs can be represented as

$$\delta_m^{t+T} = \delta_1^{t+T} + \delta_2^{t+T} + \dots + \delta_m^{t+T} \quad (3.19)$$

If, at time $(t+T)$, the generation capacity is ∂_{t+T} and the supply is S_{t+T} then minimize the difference between the supply and peak demand of P_{t+T} . Thus, the minimization problem can be expressed as

$$\min \left(\sum_{t+T}^{L_p} P_{t+T} - S_{t+T} \right) \quad (3.20)$$

Here, L_p is the time slot during the peak hours. Subject to

$$S_{t+T} = \partial_{t+T} + \delta_m^{t+T} \quad (3.21)$$

And

$$S_{t+T} \geq \frac{E_n^{t+T}}{\lambda} \quad (3.22)$$

Where, E_n^{t+T} is the energy consumption of n user at the peak hour.

B. Energy Scheduling Algorithm

Based on the predicted demand and status of available PEV power, Algorithm 3.2 uses a greedy approach to finalize the power discharge queue of different aggregators. This schedule is sent to the WLAN APs to initiate PEV discharge to store the energy in local power banks. The algorithm builds a solution by going one step at a time through the feasible solutions, applying a heuristic, which is the largest value, to determine the best choice.

3.2.3.2. Communication Network Model V2G load management scheme

SG interoperability and heterogeneous communication are defined by the IEEE2030 standard. According to the standard, a NAN can act as a DAP for links to the meter data management system (MDMS). For the proposed V2G SG application WLAN and WiMAX will be used to provide NAN and WAN capability. According to [155], by using a dual mode WiMAX/WLAN router (WWR), the

networks can be physically separated, and no modification will be required for the WLAN stations and WiMAX Base Stations (BS). A detailed performance analysis of the WLAN-WiMAX heterogeneous network for SG applications can be found in [155].

Algorithm 3.2. PEV Discharging Scheduling Algorithm

Input: P_D (Predicted 24-hour demand), S (Supply Curve as per Capacity), δ (vector PEV capacity for different APs)

Output: Generate γ (schedule vector for APs to discharge to the grid. $\gamma[i] = t$ means i^{th} AP will contribute to the grid from its storage at t^{th} time).

1. load P_D, S_D, δ
 2. set $\Delta = 0$
 3. for $i = t, t + 1, t + 2, \dots, t + 24$
 4. If $P_D[t] \geq \partial[t]$
 5. $\epsilon[t] = P_D[t] - \partial[t]$
 6. while (δ in not empty && $\Delta[t] < \epsilon[t]$)
 7. $\text{temp} = \max_{i=1 \sim n} \delta$
 8. if ($\Delta[t] + \text{temp} \leq \epsilon[t]$)
 9. $\Delta[t] += \text{temp}$
 10. set $\gamma[i] \leftarrow 1$
 11. set $\delta[i] \leftarrow 0$
 12. end if
 13. end while
 14. end if
 15. End for
-

The proposed V2G system comprises four node types including a PEV discharging Control Centre (CC) located at the utility CC, Aggregators, PEVs and the vehicle owner's cellular device. The CC operates an energy scheduler for efficient budgeting of aggregated energy. To implement the energy scheduling algorithm, the CC uses the communication network to update the status of aggregators with their associated State of Charge (SoC) and automatically perform switching to initiate discharge, based on the proposed algorithm.

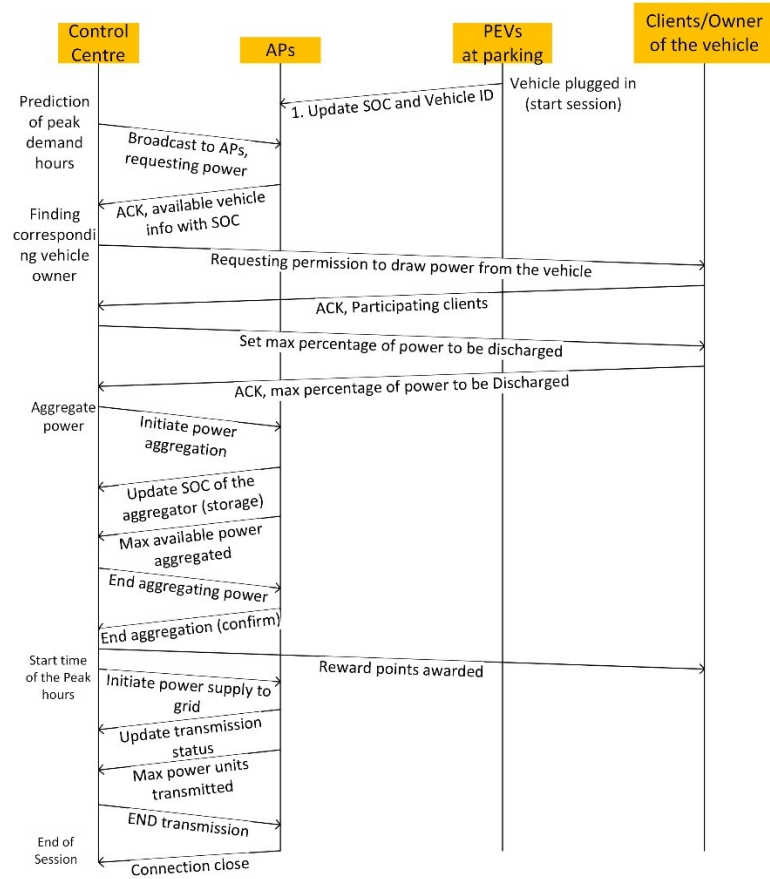


Figure 3.9 Message exchange during the aggregation and discharging session

Figure 3.9 shows the message exchange during the aggregation and discharging session. Once the vehicles are plugged-in at the discharging stations of the customer premises, corresponding vehicle id, owner details (e.g., name, cell number), battery size, rated capacity, SOC, etc. are updated to the CC via WLAN APs. In the next step, based on the predicted peak demand analysis and required supply to meet that demand, the CC measures the amount of power available to be drawn from the aggregator's power bank. Before initiating aggregating power, the CC sends an authentication request to each vehicle owner and sends a command to the APs to initiate vehicle power discharge to the amount set by the vehicle owner. Upon receiving the energy allocation, the aggregator starts drawing power from the PEVs. Then, via a periodic message transmission, the APs update the aggregator's SoC. Additionally, the CC notifies participating vehicle owners of any additional rewards for further power discharge from their vehicles.

Note that, aggregation is carried out well ahead of the beginning of the daily peak demand to ensure

the vehicle discharge has time to occur. The battery discharge duration is also considered while initiating power aggregation. During the start of the peak demand period, the CC sends a supply request to the aggregator specifying the energy required to meet peak demand. Power is fed to the grid and supply is maintained until the demand curve is satisfied. Periodic SoC updates of the aggregator are sent to the CC, and at the end of the peak hour, the CC sends ‘end session’ messages to the APs to terminate the V2G power supply. The total communication cost of the proposed V2G application can be presented as

$$C = C_a + C_b + C_c \quad (3.23)$$

Where C_a is the communication cost for initializing scheduling, C_b is the communication cost during discharging from APs to CC, C_c is the communication cost between PEVs and APs. Here

$$C_a = \eta * C_\alpha + C_\beta * \eta * \sum_{i=0}^n x_i \quad (3.24)$$

Where, x_i is the number of PEVs, η is the number of APs, C_α is the communication between each AP and CC, C_β is the communication cost between CC and vehicle owners (cellular network). And

$$C_b = \eta * C_\gamma \quad (3.25)$$

$$C_c = \eta * \sum_{i=0}^n x_i * C_\varphi \quad (3.26)$$

Where, C_γ is the rate of status updates between APs and CC during discharging process, C_φ is the communication cost between a PEV and AP. Thus, (3.23) becomes

$$C = \eta * [C_\alpha + (C_\beta + C_\gamma) * \sum_{i=0}^n x_i + C_\varphi] \quad (3.27)$$

3.2.4. Performance analysis of HetNet based V2G load management scheme

In this section, performance analysis of the Heterogeneous network based V2G load management scheme is presented. An OPNET simulation model was developed where a single cell WiMAX network covering 20 WWR enabled routers aggregate information from the smart meters installed at twenty different parking spaces. Each parking location can accommodate a maximum of 500 PEVs. To model vehicle arrival patterns three different ‘parking time windows’ (PTW) were considered

starting from 12 am to 8 am (1st PTW) following by 8 am to 4 pm (2nd PTW) and 4 pm to 12 pm (3rd PTW). In the 2nd PTW most of the PEVs arrive, and a Pareto distribution function [186] is used for modeling PEV arrival patterns where 90% of the PEVs will be plugged into the system within the first hour of the PTW. The battery size is considered to be 15KWh for all of the PEVs with a rated capacity of 80%. The discharging characteristics, the configuration of the charging/discharging station, voltage drops or associated losses were not taken into consideration as these parameters do not fall under the scope of this study and are left to be included in future work.

Table 3.3 and Table 3.4 provide the simulation parameters for the V2G and HetNet models. The grid has a capacity of 5000KWh. Based on statistical data [187] we considered the peak demand hours between 6 pm to 9 pm and from 11 pm to 12 am.

Table 3.3 V2G simulation parameter

<i>V2G Parameters</i>	<i>Details</i>
Number of APs and Parking spaces	20
Number of WiMAX BS	1
Max Grid Capacity	5000KWh
PEV to AP traffic (NAN-WLAN)	8 pph
AP to CC traffic (WAN-HetNet)	8 pph
V2G status update traffic (WAN-HetNet)	60 pph
Power Bank (Lithium Ion) storage [14]	1MW

Table 3.4 HetNet Simulation parameters

<i>WLAN_Parameters</i>	<i>Details</i>	<i>WiMAX Parameters</i>	<i>Details</i>
Standard	802.11	Standard	802.16
Frequency	5GHz	Frequency	2.3 GHz
Bandwidth	20 MHz	Bandwidth	20MHz
Physical Layer	OFDM	Physical Layer	OFDMA (FFT 2048)
Data Rate	54Mbps	Channel capacity	12.4 Msps

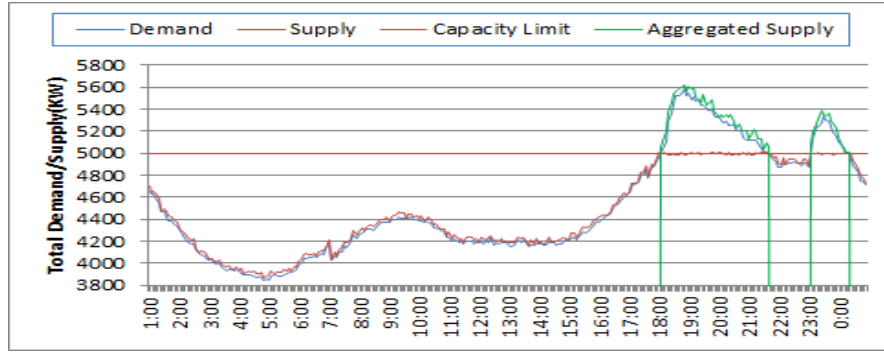


Figure 3.10 Power Supply during peak hours with aggregated power from PEVs

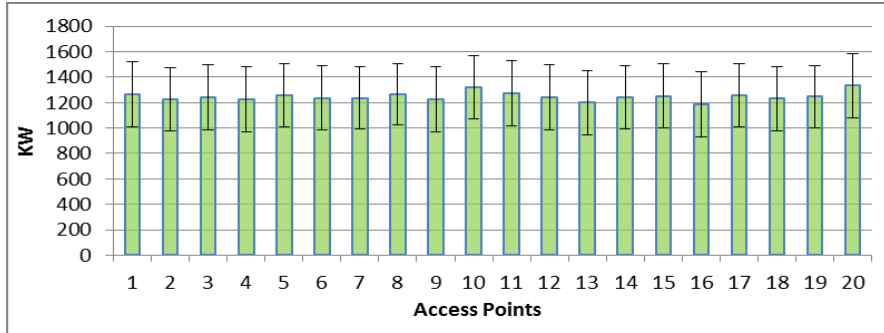


Figure 3.11 Aggregated power from different aggregation points

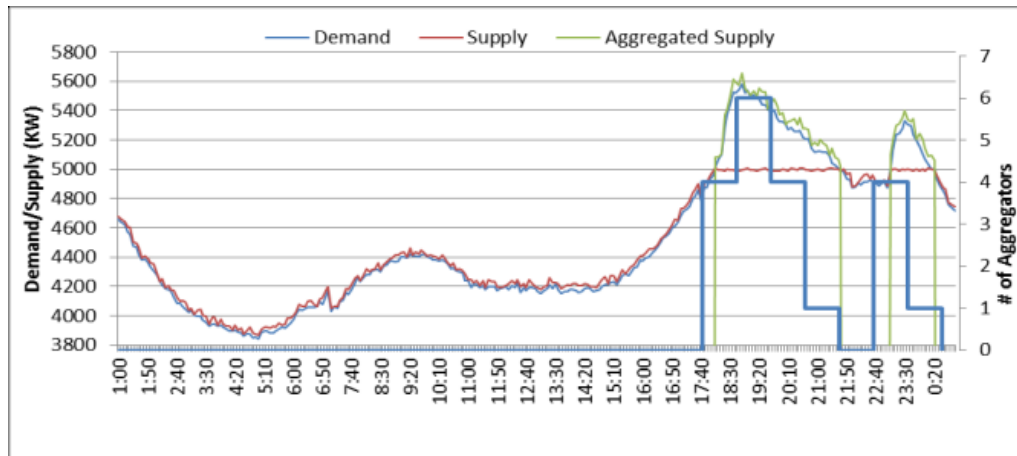


Figure 3.12 Number of aggregators required to meet the peak demand

Figure 3.10 shows that the proposed energy scheduling successfully aggregates enough power to meet the requirement during the peak hours. Figure 3.11 shows the amount of power that could be drawn from different parking locations. It can be seen that from 20 such parking locations approximately a total of $(1275 \times 20 = 25500 \text{ kW})$ 2.55 MW can be stored in the aggregator's power bank.

At the beginning of the peak hour, the CC sends requests to the APs to initiate power release to the grid from their power banks. In Figure 3.12, with a secondary y-axis representation, the blue step curve shows the number of aggregators required to meet the peak demand.

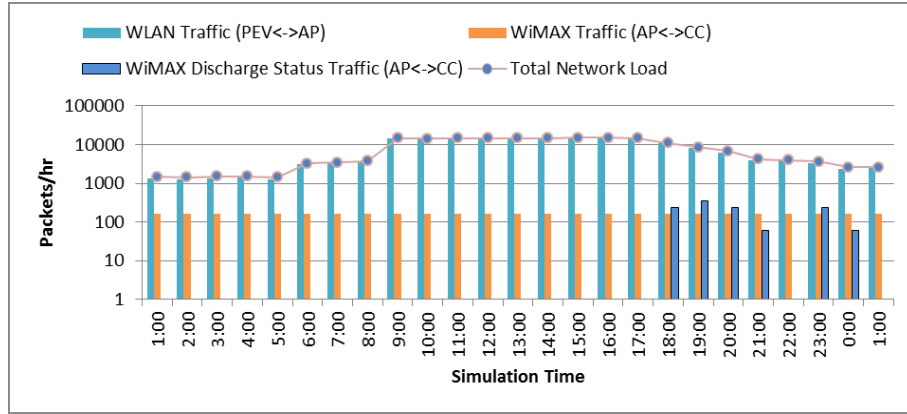


Figure 3.13 Total communication load in a single day

SG applications such as V2G are moderately delay sensitive but should be highly reliable. Thus, detailed analysis of the communication traffic load is a very important performance metric. Daily total communication network load is shown in Figure 3.13 on a logarithmic scale. Communication traffic model parameters are shown in Table 3.3. When the CC starts drawing power from the aggregator's power banks, AP commence sending periodic SoC updates (WiMAX discharge traffic status) to the CC during the start of the peak hour (6.00pm). Also, there is a noticeable increase in the WLAN traffic (PEV to AP) from 9 am as more PEVs get plugged in the morning and stay parked until the end of office hours (5 pm).

3.3. Advanced ranging scheme for WiMax

WiMAX has emerged as one of the leading access technology candidates for the next generation SG because of its high capacity, wide coverage, high bandwidth and built-in QoS and robust security capabilities [188][189][41]. In a SG paradigm, the role of WiMAX is being envisaged as a WAN supporting communications between the control center and a large number of devices such as smart meters and field sensors [190].

While typical WiMAX networks have been optimized for low latency VoIP calls and high bandwidth video and gaming applications, the communication requirements for SG networks are entirely different. Based on traffic characteristics [191], the SG applications can be categorized into two broad groups, time-triggered and event-triggered. They can be further divided into two types, delay sensitive

and delay tolerant. For example, smart metering traffic is time-triggered and fairly delay tolerant whereas the traffic from field sensors is event-triggered and can be highly delayed sensitive. Since the number of devices that access the network at any given time depends on the active applications, the random-access load of a SG network will be influenced by an event in the grid [34].

The standard network entry procedure of WiMAX technology is based on Code Division Multiple Access (CDMA) ranging [192]. In addition to providing random access, the ranging process enables a Subscriber Station (SS) to acquire uplink synchronization, control transmit power and perform bandwidth requests. Thus, it plays a crucial role in determining the overall system performance. The existing WiMAX ranging mechanism is a contention based procedure where multiple subscriber stations are allowed to collide in an OFDMA subchannel for a network access opportunity using a set of orthogonal CDMA codes [193][194].

In this section, a novel ranging scheme is proposed that can provide contention free network access to the periodic M2M applications in the SG. First, the performance of existing WiMAX ranging channel at different random access loads is evaluated using a discrete event simulation model based on OPNET Modeler v16.0. Next, a ranging scheme for periodic M2M applications is presented with an explanation on the key features. Finally, a SG event is simulated where the underlying WiMAX network faces a heavy random-access load and compare the performance of our proposed scheme with that of the conventional ranging scheme.

3.3.1. The WiMAX Ranging Procedure

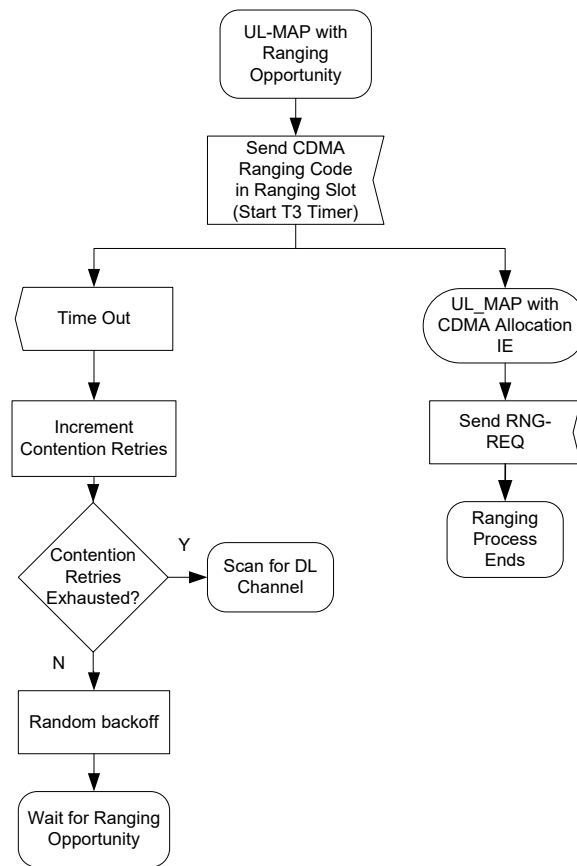


Figure 3.14 Flow diagram of the WiMAX ranging procedure

Upon successfully receiving a ranging code, the BS broadcasts a ranging response (RNG-RESP) message that advertises the received ranging code and the ranging slot (shown in Figure 3.14). This information is used by the associated SS to identify the RNG-RESP message which provides all of the adjustments required, e.g., time, power, and possibly frequency corrections. On the other hand, if a BS receives a ranging code that does not require any correction; it provides the bandwidth allocation for the SS using the *CDMA_Allocation_IE* to send a ranging request (RNG-REQ) or a bandwidth request (BW-REQ) message. More details of the ranging procedure can be found in [194][195][196].

Collisions occur when two or more SS select the same ranging slot or code. To resolve contention, SSs use the truncated Binary Exponential Backoff (BEB) procedure with the initial and maximum backoff windows controlled by the BS. The SS randomly selects a number within its backoff window which indicates the number of contention transmission opportunities that the SS shall defer before

transmitting. After a contention transmission, the SS waits for a *CDMA_Allocation_IE* in the subsequent MAP (or waits for an RNG-RSP message for initial ranging). Once received, the contention resolution is complete.

The SS considers the contention transmission lost if no data grant IE has been received within a set timeout. In that case, the SS increases its backoff window by a factor of two (as long as it is less than the maximum backoff window), randomly selects a number within its new backoff window and repeat the deferring process described above. This retry process continues until the maximum number of retries has been reached.

3.3.2. Performance Analysis of Ranging Procedure

To evaluate the performance of the ranging channel a simulation was used to identify that successful detection of a single ranging code is enough to provide network access. It was assumed that the BS could detect a ranging code successfully only when a single SS transmits a ranging code on a ranging channel. If more than one SS transmits the same ranging code, the BS can't detect any of them. The other simulation parameters are provided in Table 3.5

Table 3.5 Ranging Simulation Parameters

<i>Parameters</i>	<i>Setting</i>
<i>No. of Ranging Channels per Frame</i>	1
<i>Back-off window Size</i>	4-16
<i>Maximum Number of Retries</i>	8
<i>BS processing latency</i>	1 Frame (5ms)
<i>Probability of Misdetection & False Alarm</i>	0%
<i>Pathless Model</i>	Suburban Fixed
<i>System Bandwidth</i>	5 MHz
<i>FFT Size</i>	512

The following metrics were defined to evaluate the performance of the existing WiMAX ranging channel

$$\text{Normalized Access Load } (L) = \frac{\text{No. of Network Entry Attempts/sec}}{\text{No. of Ranging Opportunities/sec}} \quad (3.28)$$

$$\text{Access Success Rate } (S) = \frac{\text{No. of Successfull Network Entires /sec}}{\text{No. of Network Entry Attempts/sec}} \quad (3.29)$$

$$\text{Access Throughput } (\theta) = \frac{\text{No. of Successfull Network Entires}}{\text{No. of Ranging Opportunities/sec}} = (\text{Access Success Rate} * \text{Access Load}) \quad (3.30)$$

Here Access Delay (D) is the time until a successful network entry. Assuming a frame duration of 5ms, there are 200 ranging opportunities available per second for a single ranging code on a single ranging channel. Hence, to determine the maximum sustainable access load of the ranging channel, the simulation model considered up to 200 access attempts/sec using a step of 10.

Each simulation was run for an hour, and the results were averaged using three different seeds. For each simulation scenario, the statistics of successful network entries and the associated delay were recorded. Using these values, we calculate the overall L, S & θ . The results are shown in Figure 3.15, Figure 3.16, Figure 3.17 and Figure 3.18.

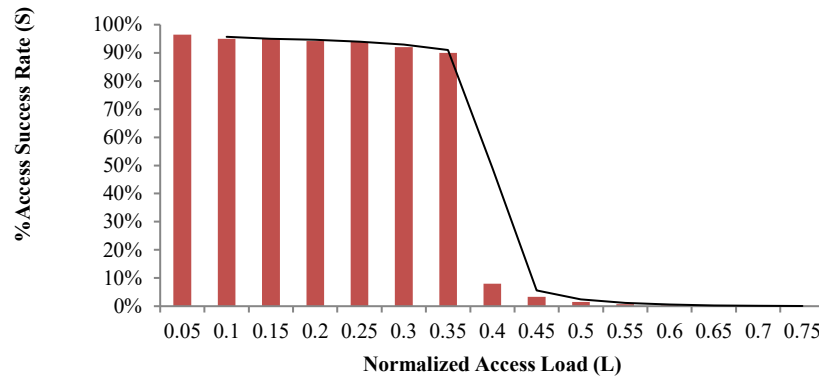


Figure 3.15 Ranging access load vs. access success rate

From the results, it can be assessed that when the load is around 35% (70 attempts/sec), the system is stable with a success rate over 90% and the delay is bounded within 120ms. After that point, the access success rate drops sharply and mean access delay increases exponentially. Also, the average number of retries reaches up to the maximum number of allowed retries (8 in this case) and hence the contending device abandons the access attempt. Thus, it can be concluded that the maximum sustainable access rate for a ranging channel with a single code is less than 70 attempts per second.

Also, it should be noted that the overall throughput of the ranging channel is quite low with the peak (32%) occurring at the maximum sustainable access load.

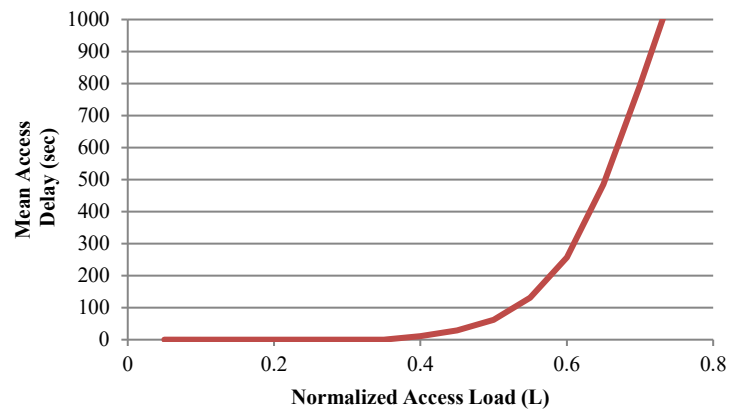


Figure 3.16 Ranging access load vs. mean access delay

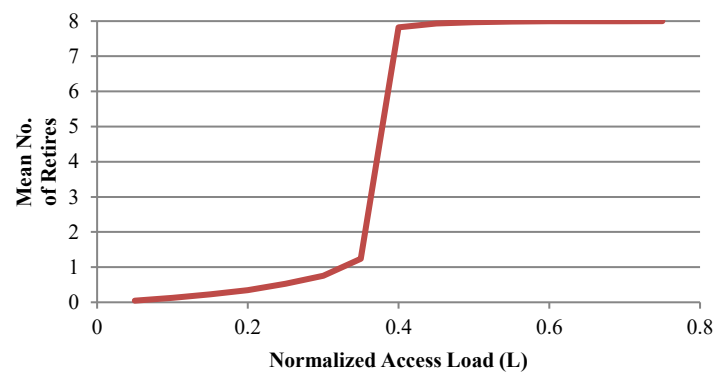


Figure 3.17 Ranging Access Load vs. Mean No. of Retires

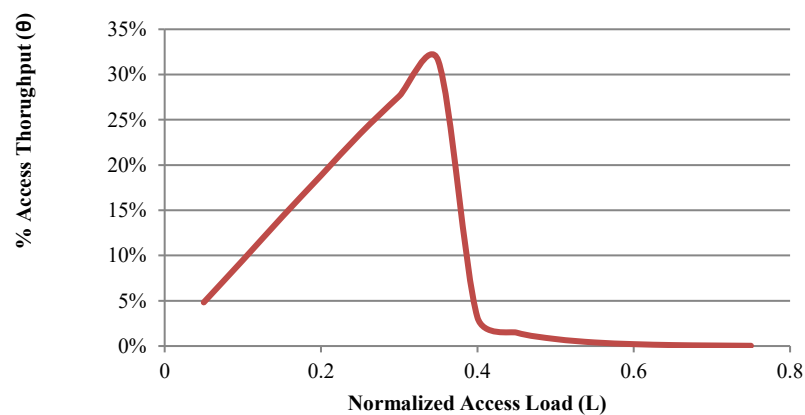


Figure 3.18 Ranging Access Load vs. Access Throughput

There are two ways to extend the capacity of the ranging channel – either increase the number of codes or increase the size of backoff window. Figure 3.19 shows the access success rate for varying numbers of ranging codes and Figure 3.20 shows the effect of different backoff window sizes on the access success rate.

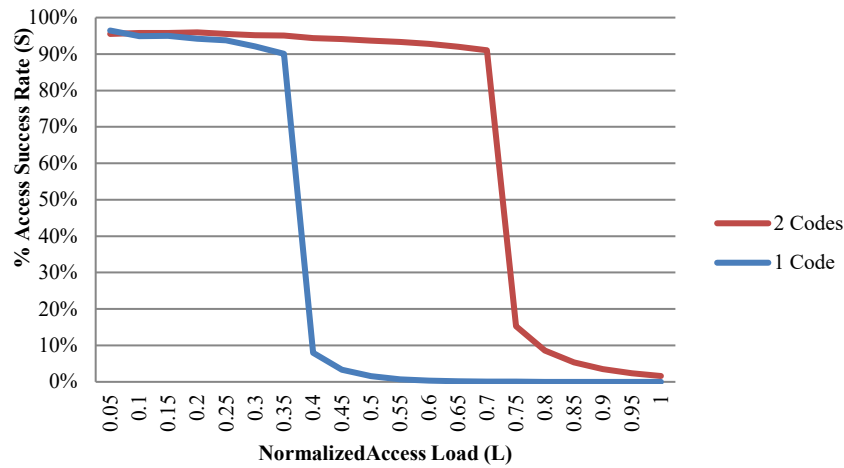


Figure 3.19 Access Success Rate for different no. of ranging codes

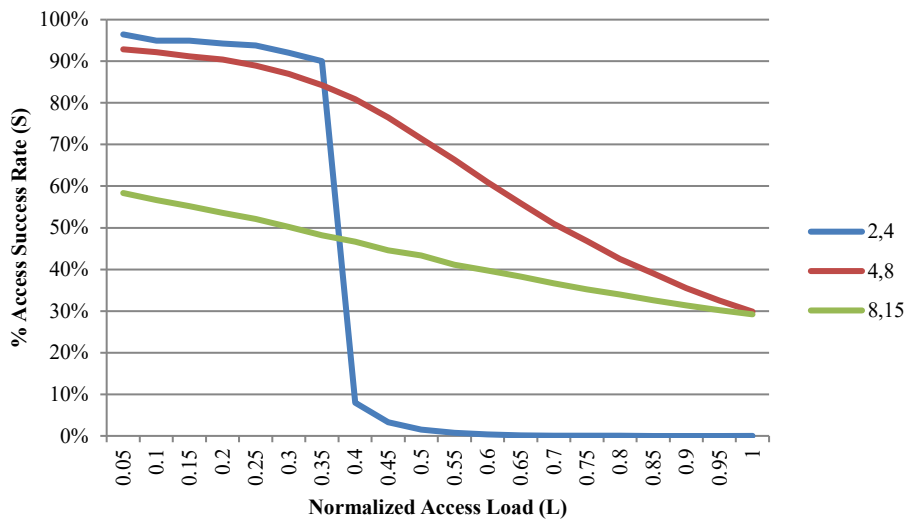


Figure 3.20 Access Success Rate for Different Backoff Window Sizes

From the results, it can be observed that the maximum sustainable access rate increases from 70 to 175 when two ranging codes can be detected instead of one. Although theoretically it's possible to use up to 256 codes in the contention process, the BS is able to detect a limited number of parallel ranging codes on the ranging channel. The BS considers a successful reception of a ranging code if the cross-

correlation of the code and the received superposition of different ranging codes exceed a set threshold. Consequently, a low detection threshold increases the number of simultaneous codes detected but also increases the probability of misdetection and false alarms [195]. Nevertheless, most of the commercially available BSs can detect at least two ranging codes simultaneously.

For larger backoff windows, the chances of successful network entry increase at high loads but comes at a cost of reduced access success rates at low loads. Nevertheless, a medium backoff window like (4, 8) can provides improved performance especially at high loads. The success rate is over 50% up to 70% of the load.

3.3.3. The Proposed Ranging Scheme

The key feature of the proposed scheme is to allocate separate ranging codes for periodic and aperiodic applications so that differentiated services can be provided based on application requirements. For example, for a ranging channel with two simultaneously detectable codes, one code can be assigned for periodic application and another for event-triggered applications. The reserved ranging code for the event-triggered applications can be used with different backoff windows like the Arbitration Inter-Frame Spacing (AIFS) method in IEEE 802.11e standard [197], to provide prioritized access during an event [198].

However, the reservation of ranging resources for event-driven applications effectively halves the available ranging resources for periodic applications and thus increases the chances of collision during network access retries. Therefore, a ranging code reuse algorithm is proposed for periodic M2M applications where the contending devices will share a dedicated ranging code in a time division mode.

According to the proposed scheme, the contending nodes are divided into N groups according to their reporting cycle T . Each group will have a set of dedicated ranging slots (τ) according to their application arrival rate (λ). The allocated ranging slots will be shared uniformly among the n member nodes of a particular group using the steps specified in Algorithm 3.3. For example, a M2M group

with an arrival rate of three reports per second will receive three ranging slots (τ_1, τ_2, τ_3) per second. The member nodes will share the three ranging slots such that every node gets a dedicated transmission opportunity (t_1, t_2, \dots, t_n) to send data within one reporting cycle ($t_{max} \leq T$). Figure 3.21 illustrates the proposed algorithm.

Algorithm 3.3 Time based Re-use of Ranging Code

Input:

T =Application reporting cycle

N =No. of M2M groups based on same reporting cycle

Output:

λ_i =Arrival rate for i^{th} M2M group, $i = 1, 2, 3, \dots, N$

$\tau_j = j^{th}$ ranging slot for i^{th} M2M group, $i = 1, 2, 3, \dots, \lambda$

$t_k = T_x$ opportunity for K^{th} node in the j^{th} slot, $k = 1, 2, 3, \dots, n$

1. **for** $i = 0$ **to** N
 2. $\lambda_i = n_i / T_i$
 3. **For** $j = 0$ **to** λ_i
 4. **If** $s = 0, \tau_j = 0$
 5. **Else** $\tau_j = s$
 6. $s++$
 7. **For** $k = 0$ **to** n
 8. $t_k = \tau_j + T_i$
 9. **End for**
 10. **End for**
 11. **End for**
-

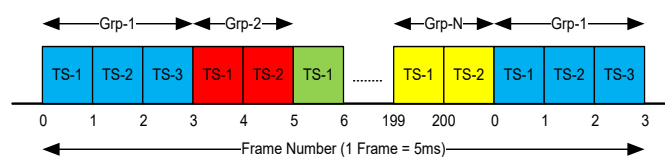


Figure 3.21 Illustration of Time based Ranging Code Re-use Algorithm

The M2M group can be assigned manually during device configuration or dynamically when joining the network. Based on M2M group assignment, the BS will allocate ranging codes, ranging slots and explicitly provide first transmission opportunity according to the proposed algorithm. The M2M device will then derive the next transmission opportunities by adding the reporting interval with the time of the first transmission opportunity and use it as the backoff value to access the network sequentially without any contention. In case the dedicated ranging opportunity fails, the M2M device will use the

contention process to access the network. Figure 3.22 describes the network entry procedure using the proposed scheme.

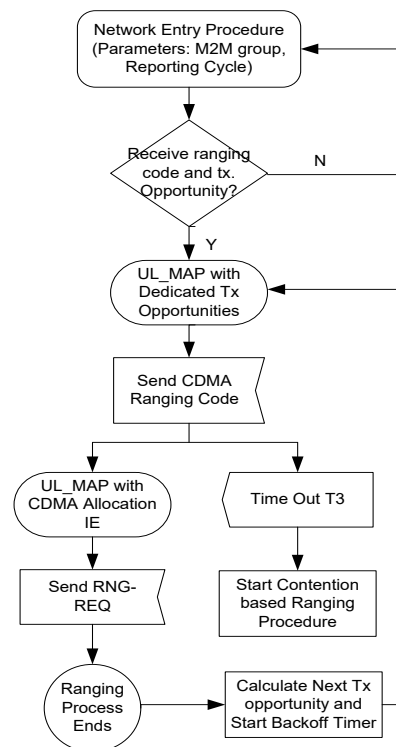


Figure 3.22 Flow Chart for Network Entry using the Proposed Algorithm for periodic applications

The access delay and throughput of the ranging channel using our proposed algorithm is shown in comparison with different backoff windows in Figure 3.23 and Figure 3.24. It should be noted that the proposed algorithm works for periodic applications only.

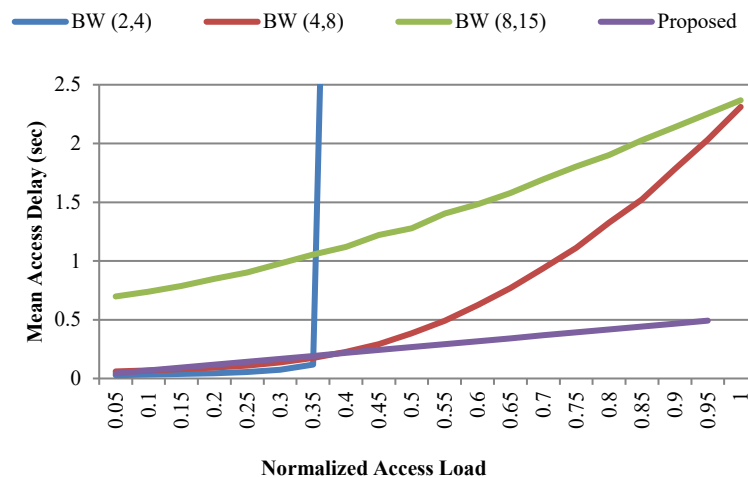


Figure 3.23 Mean access delay of the proposed scheme

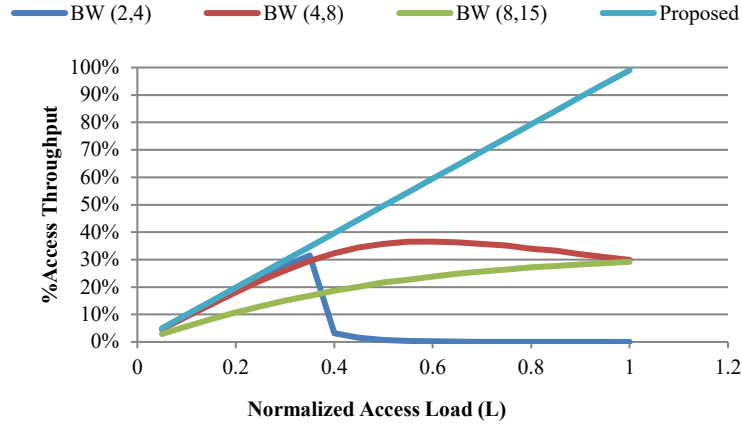


Figure 3.24 Mean access throughput of the proposed scheme

From the results, it can be seen that for periodic applications the proposed algorithm provides improved delay and throughput performance than that of the other schemes. The performance graph is linear and stable at high access load since it provides contention free access to the participating devices.

3.3.4. Performance analysis of Proposed WiMax Ranging Scheme

To evaluate the performance and effectiveness of the proposed scheme, a simulation model was developed using OPNET Modeler v16.0. The simulation scenario includes 15K nodes consists of smart meters for household, business and EV applications and sensors for environmental monitoring, PMUs and SCADA RTUs. The model further simulates a grid event where a distribution feeder supplying 50 smart meters experiences a short circuit fault. The feeder also contains ten field devices and 20 environmental sensors. During the event, all the field devices send protection messages, the environmental sensors send alarms, and the smart meters reports an outage with in an interval of one second.

Two independent scenarios were simulated. The first scenario used a conventional ranging scheme whereas the other one used the proposed scheme. The simulation used the same parameters and assumptions specified in Section 3.3.2 except that the BS can detect two ranging codes simultaneously. Also, for the second scenario, three different backoff windows were used for the events to give prioritized network access. The simulation was run for a five-minute duration. The fault event occurs

at the third minute of the simulation run-time. The summary of the applications and events are shown in Table 3.6 and Table 3.7.

Table 3.6 Simulation Settings for Periodic SG Applications

<i>App. Details</i>	<i>No. of Nodes</i>	<i>Inter-arrival Time (sec)</i>	<i>Arrival Rate /App./sec</i>	<i>Required Latency (sec)</i>
Metering-Household	9000	1800	5	900
Metering-Business	1500	60	25	300
Metering –EV	3000	300	10	10
Monitoring– Environment	1200	300	4	60
Monitoring– RTU	250	10	25	5
Monitoring– PMU	50	1	50	1
Total	15000	-	119	-

Table 3.7 Simulation Settings for the SG Event

<i>Event</i>	<i>No. of Nodes</i>	<i>Arrival Rate</i>	<i>Required Latency</i>	<i>Backoff Window</i>
Protection Messages	10	10	100ms	1,2
Critical Sensor Alarm	50	10	250ms	4,5
Meter Outage Report	500	50	500ms	5,8

The system performance was evaluated using overall network delay and individual application response time. While the delay profile provides information about the of stability of the whole network, the application response time provides insights into the performance of the ranging channel as it incorporates both the effect of access success rate and access delay. The results are summarized in Figure 3.25 and Figure 3.26.

Figure 3.25 shows delay profile of the conventional scheme, although the event occurs for a second, the whole network become unstable after the event. This is because the number of access attempts exceeds the maximum sustainable access rate which in turn congests the entire ranging channel. The proposed scheme is able to handle the event successfully.

Figure 3.26 shows that the conventional ranging process fails to meet the maximum latency requirements specified in Table 3.6. This is because the ranging resources are shared among all of the applications, and no prioritization is used. The proposed scheme provides a low average delay since it not only conserves the ranging resources but also provides prioritized network access based on the

application requirements, as shown in Table 4.6.

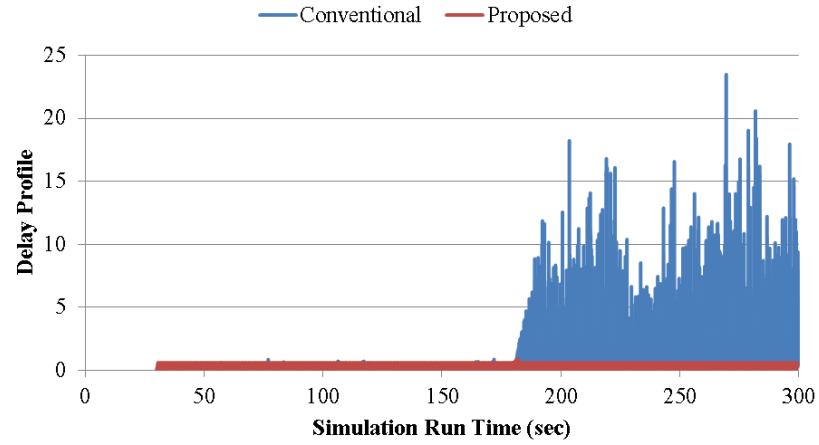


Figure 3.25 Delay profile of the simulation scenario

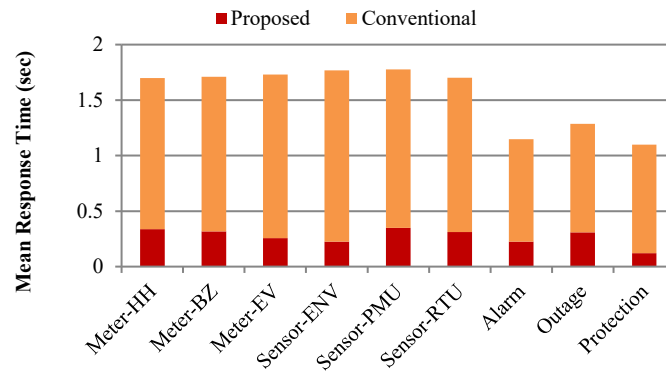


Figure 3.26 Mean application response time

3.4. Summary

The chapter has presented two novel SG application models. The models include design of the end-to-end network architecture, traffic dissemination model and novel algorithm. The first application presents the Zigbee based pilot protection scheme. An IEEE 802.15.4 Zigbee based wide area SG communication network has been developed and a proposed Demand Based Priority Queuing technique is used to provide reliable and high-speed delivery of the pilot protection signals. For high-speed M2M communication between protection relays, the IEC 61850-90-5 based GOOSE protocol has been considered.

The second application presents efficient mechanism to handle a large number of PEVs and

establishment of a robust and reliable communication network for short burst transmissions. The study proposes an end-to-end load management scheme to enable V2G power transmission based on a WiMAX WLAN hybrid network architecture in SGs and considers the case of peak power via discharging PEVs with small energy bursts while WiMAX-WLAN network efficiently deals with flexible data aggregation to reduce signaling and protocol overheads. A novel energy scheduling algorithm is presented for an efficient admission control process and to deal with variable energy budgeting within a specific timeframe. On the other hand, the V2G grid load management scheme presents successful demand resolution via proposed prediction based load management scheme. The communication network load is also shown.

The overall performance of WiMAX based SG communication networks strongly depends on the performance of its network access mechanism. While the standard WiMAX ranging procedure serves conventional multimedia applications, the requirements for SG networks are unique and application specific. Therefore, the proposed WiMAX ranging scheme focused on the analysis of the impact of SG applications on the WiMAX ranging channel. This study evaluated performance of the existing WiMAX ranging channel at different network access loads. Simulation results analysis demonstrate that for a single ranging subchannel with a single ranging code, the system can serve up to 70 access attempts per second within an acceptable delay. The capacity of the system can be further increased by using additional codes or a larger backoff window. However, during grid events, the random-access load can increase abruptly congesting the ranging channel. Therefore, a novel ranging scheme for periodic M2M applications in a SG was presented. Using a discrete event simulation, a SG event was simulated, and the proposed scheme demonstrated that it could effectively handle the additional random access load during a SG event.

CHAPTER 4. SDN based SG NAN framework

4.1. Overview

Major contributions presented in this chapter address research question 2. The premises located in a NAN of the SG play vital role in collecting raw data that could be used in diverse application modelling. An SDN based NAN would require the appropriate choice of wireless communication technology that can efficiently collect information from the IEDs, sensory devices or SMS. A novel communication framework is presented that exploits SDN networking concept in WSN and modelled to fit SG NAN domain. Particularly, the motivation of this study is to enable SDN based M2M communication-based on the NAN domain. Also, the study identified the need of optimized number of distributed controllers within the NAN domain. Details of the communication framework, network configuration and access mechanism have been provided that support diverse SG applications using a SDN based network. Different NAN based SG applications are considered and analyzed by creating appropriate traffic models in SDN. Furthermore, extensive simulation based outcomes and statistical analysis have been carried out to demonstrate the feasibility of the proposed framework. Statistical data sets from load supply profiles are widely utilized to develop realistic simulation models. This dataset requires statistical analysis using the statistical analyzer. In this study, Matlab Statistical Toolbox has been extensively used to analyze the derived simulation data. The major advantage of this method is that it is designed to apply to a wide range of environments based on the SG traffic characteristic.

4.2. Network Architecture of the SDN based NAN

The literature review, Section 2.8, highlighted that research on WSN and SDN based NAN is still in its infancy. The system design for the proposed framework considers the specifications released by the TG4g task group and was motivated by the potential for SDN based M2M communications across the NAN domain. Figure 4.1 shows the conceptual architecture of the SDN based NAN. The sensor nodes are deployed in the customer premises of an SG to create Home HAN, BAN or IAN. Overall, with several HANs, BANs, and IANs a single NAN is created. Within a NAN, the sensor nodes are

connected to associated switches, and the switches are connected to centralized NAN controller that also serves the NAN gateways. Each switch associates themselves with the closest SDN controller to retrieve the packet forwarding instruction. Packet dissemination control information is guided via a set of rules called flow commands provided by the SDN controller. Furthermore, each NAN is attached to an SDN NAN controller, and all the NAN controllers are connected to single NAN domain controller which also acts as the gateway.

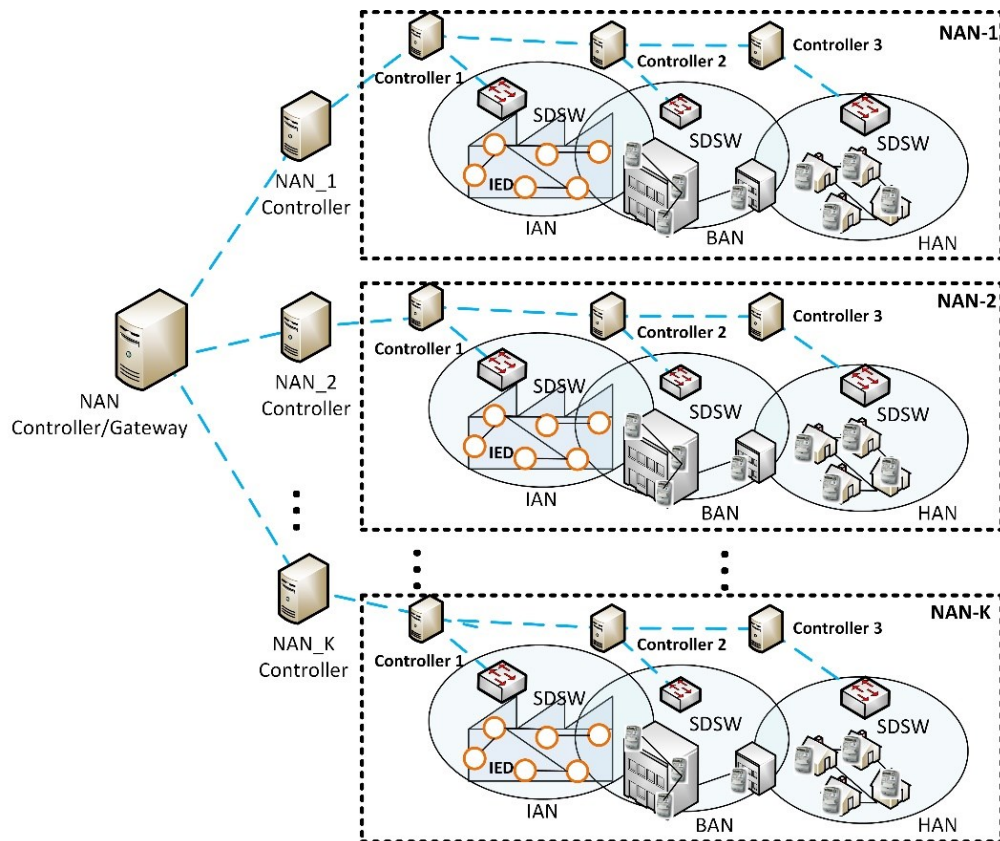


Figure 4.1 SDN based WSN to support NAN architecture

4.3. Framework configuration

SG NAN and FAN applications mostly fall under AMI or smart meter based and usually semi periodic in manner. For example, AMR, DM, EV charging/ discharging, micro-grid management, etc. DR is responsible for balancing the load between generation plant and consumers via implementing diverse load control programs. The load control could be based on dynamic pricing of the energy units or more advanced technique of RLC. An example of well-known dynamic price programs is TOU, RTP, CPP, PTR. On the other hand, characteristics of an RLC program can vary based on properties such as

interruptible loads, reducible loads, partially interruptible loads. More details on these DR programs could be found in [199]. DA [200] should be designed for providing near real time information on grid operation to better the monitoring and control within the distribution grid. With a large number of DERs, it becomes more important. Because by utilizing the distribution level devices such as voltage regulators, fault detectors, capacitor bank controllers (CBC), reclosers, etc. A DA system can enable useful applications like Volt/VAR control, fault detection cleaning, isolation and restoration (FCIR) and distribution system monitoring and maintenance. Volt/VAR control adjusts the voltage and balances the load factor to reduce the energy loss. In distribution monitoring and maintenance, sensor data is used to monitor the status (open/closed) of various distribution grid equipment. With FCIR, a section of the grid could be isolated if there is an occurrence of a fault and automatic restoration system can be set up to minimize service interruptions.

A meter reading application can send scheduled meter data to the controller via Smart Meters installed in the customer premises. Both controller and customers could use the data for billing inquiries and verify outage and restoration events. Also, meter data could be generated to monitor the health status of the smart meter (e.g. connection status, hardware configurations), on grid events (e.g. software upgrades), or to generate event alarms (voltage distortions, outage, scheduled maintenance). In the case of an outage event, an outage management application needs to send the ‘last gasp’ alarm from the affected smart meters to the control center. As there will be no power accept the charge stored in the capacitor of the affected smart meter, outage alarms are required to be transmitted within few 10’s of millisecond [201]. So, it’s crucial to meet such requirements when a large number of smart meters would be trying to access the network simultaneously. Based on the report [202], in rural, suburban and urban areas the meter density could be 100, 800 and 2000 per Km² respectively. Table 4.1 summarizes the properties of four major SG applications in the NAN domain and shows their communication requirements. Based on the delay variability of these applications the existing SG AMI applications are categorized into two groups such as delay sensitive and delay tolerant applications.

Application characteristics and requirements [202] are also summarized.

Table 4.1 Major SG application within NAN domain

<i>AMI applications</i>	<i>Characteristics</i>	<i>Data Sending Interval</i>	<i>Data Rate</i>	<i>Data Size (bytes)</i>	<i>Delay</i>	<i>Reliability</i>
Outage management	Event based, Delay Tolerant	1 per meter per power lost	56kbps	25	2s	>98%
DR	Semi periodic (Delay tolerant)/Event based (Mission Critical)	1 per device per Broadcast request	14-100kbps per node	100	500ms-1min	>99.5%
DA	Semi-Periodic, Delay Sensitive	1 per device per 12 h	9.6-56kbps	150-200	25 _ 100 ms	>99.5%
Meter reads	Periodic, Delay Tolerant	5min, 10min, 15min, 30min, 1Hr	10Kbps to 128Kbps	200	2-15s	>98%

4.4. Communication Model

The first task towards developing the framework of the SDN based SG NAN using WSN is to determine the control and data plane characteristics. At the time of network initialization, flows are defined via the controller and stored in the switches. These flow commands are stored permanently in all switches until the corresponding applications are active in the network. Figure 4.2 (a) shows the Message exchange between network devices. As shown in Figure 4.2 (a), there are two delay tolerant SG application packets generated from the IEDs and smart meters. Upon arriving at the switch, packets are placed into a flow lookup queue. If the flow is matched with a flow stored in the flow table, the corresponding switch forwards the packet to the desired destination by placing the packet into the *immediate buffer* queue. Application layer packet flow protocol is shown in Figure 4.2 (b). If the flow is not matched, the packet is sent to the nearest controller requesting a flow control instruction be assigned. After retrieving a flow command for the packet, the packet is placed into the buffer responsible for handling missed packets and forwarded to the destination at the earliest opportunity. Note that, flow commands could be modeled in such a way that switches can unicast, multicast or broadcast the packet based on the SG application specification.

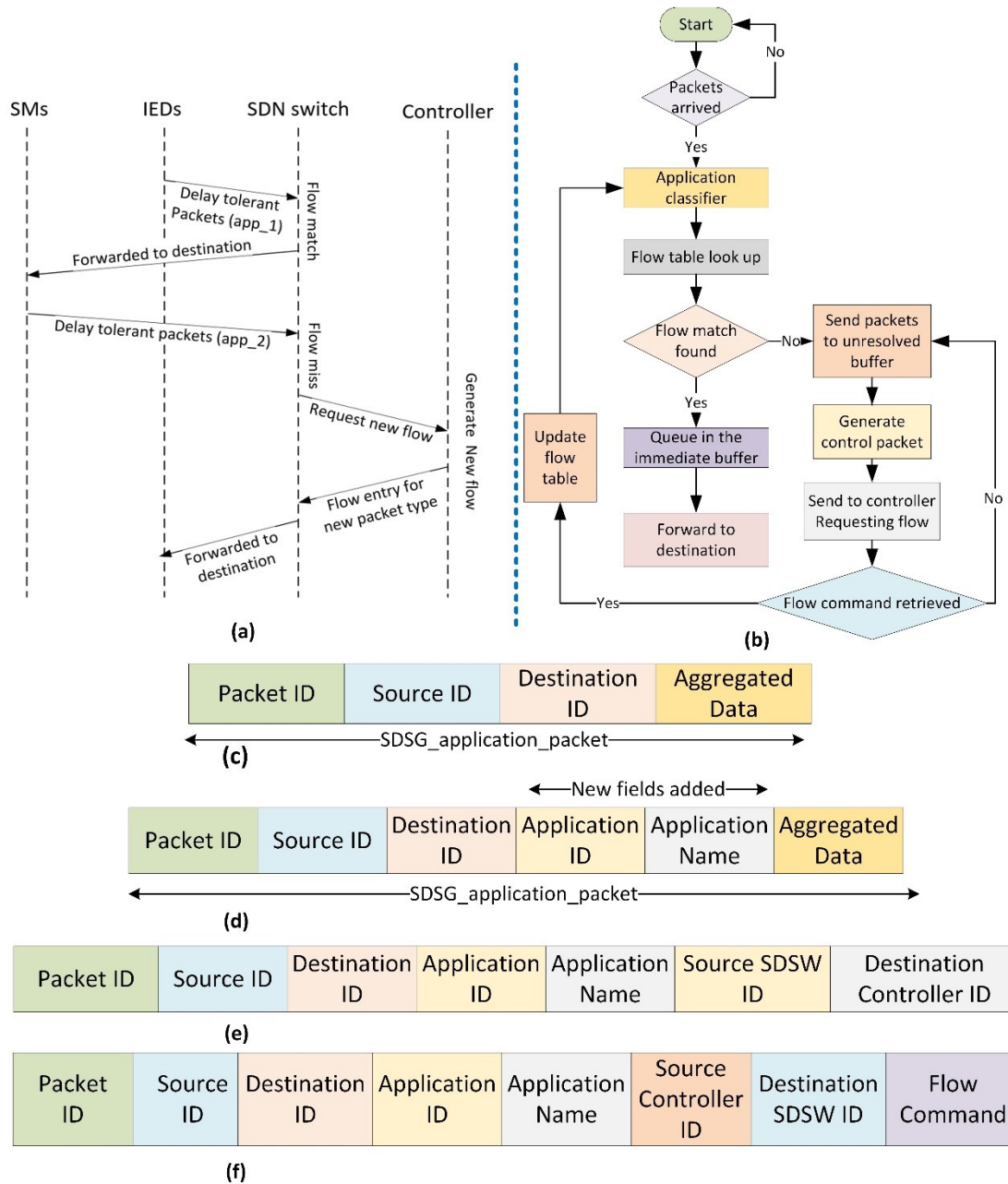


Figure 4.2 Message exchange between network devices and packet format at different stages

Data from the smart meters is sent to the switch via unicast packet transmission. The packet format of the unicast packets of the application layer is shown in Figure 4.2 (c). Upon receiving this packet, the switch uses an application classification module to determine the application name and identification number. Packet format after application classification is shown in Figure 4.2 (d). Next, the switch tries to look up for a flow match in the flow table. If the flow is found, the related action corresponding to this flow is performed. The packet is treated as resolved and sent to the network layer. In the case of a table miss event, at first, the switch inserts the packet into the queue of an unresolved buffer. Next, a

control packet is generated which containing the preamble fields of the SDSG (software defined smart grid) application packet. This packet is called ‘*Packet_In Request*’ and sent to the controller containing only the packet header fields. Packet format with flow command request to the controller is shown in Figure 4.2 (e). Only header fields of the packet are sent to avoid overloading the control channel. Upon receiving the control packet, ‘*Packet_In Request*’ (Figure 4.2 (e)), the controller replies to the corresponding switch with a new flow command by attaching a new field in the acknowledgment packet. This packet is called ‘*Packet_out Response*’ and contains the flow command to the switch. SDSG application packet with new flow command is shown in Figure 4.2 (f). At this stage, the switch updates its existing flow table and immediately forwards the packet to the destination. Algorithm 4.1 and Algorithm 4.2 summarize the entire process.

Algorithm 4.1: Application classifier module at the application layer of the cluster switch

```

input: Read  $SDSG_{gen\ pk}$ 
12. if  $pk_{val} < 0$  then
13.    $pk_{val} \leftarrow A1, A2, \dots, An$ 
14.    $new\ pk_{app\ id} \rightarrow SDSG_{gen\ pk}$ 
15.    $new\ pk_{app\ name} \rightarrow SDSG_{gen\ pk}$ 
16.    $set\ new\ pk_{app\ pk} = SDSG_{gen\ pk}$ 
17.    $SDSG_{app\ pk} \rightarrow pk\ forward\ buffer$ 
18. else  $pk\ destination \rightarrow Controller$ 
19. end if
20. initialize flow table query
21. move  $SDSG_{app\ pk}$  from queue
22. read  $app_{id}$  and  $app_{name}$ 
23. if  $app_{id}$  and  $app_{name} = true$  then
24.   Get Action
25.   if  $int\ i$  then
26.     for  $i=0, i < action, i++$  do
27.        $set\ pk\ destination$ 
28.     end for
29.   end if
30.   if  $int\ j$  then
31.     for  $j=0, j < action, j++$  do
32.        $set\ pk\ destination\ '-1'$ 
33.     end for
34.   else  $SDSG_{control\ pk} = Preamble + SDSG_{app\ pk}$ 
35.   end if
36.   else Drop pk
end if

```

In the control plane of the SDN-based NAN, SG applications could be configured and modified via the controller. The primary task of the controller is to provide flow control message to the switches. Inserting new applications or updating applications is carried out by the controller. First, updates are disseminated to all other controllers, and then updates are pushed to the application-classifier module of the switch. Considering the fact that the proposed framework operates in WSNs, an association process of the controller to the SDSW is handled based on the Received Signal Strength Indicator (RSSI) and Round-Trip Time (RTT). Theoretical details on the controller association process could be found in [203].

Algorithm 4.2: Handling packets with forwarding instruction provided to the controller

1. **Read** $SDSG_{control\ pk\ reply\ pk}$ fields
 2. **Get** app_{id} app_{name} **Action**
 3. **Set** $New\ flow = Action$
 4. **Set** app_{id} and $app_{name} \rightarrow New\ flow$
 5. **for** $i=1, i < unsolved_queue$ **do**
 6. $temp_{pk} = unsolved_queue[i]$
 7. **if** $app_{id} = temp_{pk_app_id}$ and $app_{name} = temp_{pk_app_name}$ **then**
 8. **Move** $temp_{pk} \rightarrow forwarding\ buffer$
 9. **end if**
 10. **end for**
-

4.5. SDN based Distribution Grid Architecture

In order to enable distributed control over a large area, a sector based grid topology has been considered. The grid topology selection for cluster communication was influenced by the configuration of the power distribution system. According to [204] distribution systems are mostly radial where a certain number of service transformers are connected to a single feeder. A sample of a distribution network architecture is shown in Figure 4.3 (a). A service transformer of 50 MVA can usually provide ten service drop connections [204]. Based on this estimation, if a radial system consists 108 service transformers, it can provide connections to 1080 smart meters. The radial system shown in Figure 4.3 (a) can be represented as an 8×12 grid where each service transformer has ten service-drop connections attached to ten smart meters. Now, if each service transformer is equipped with one SDN switch and

responsible for an individual sector, it can be concluded that there are 108 sectors. The distribution feeder is connected with service transformers and distributed in a radial manner. Each service transformer then delivers power to the home premises. Figure 4.3 (b) shows a section of the customer premises where each home is connected to the service transformer via individual service drop. Smart meters and IEDs are installed at each home and aggregate data for further processing. The meter data is sent to the corresponding switches and forwarded to the appropriate authority to enable various SG applications.

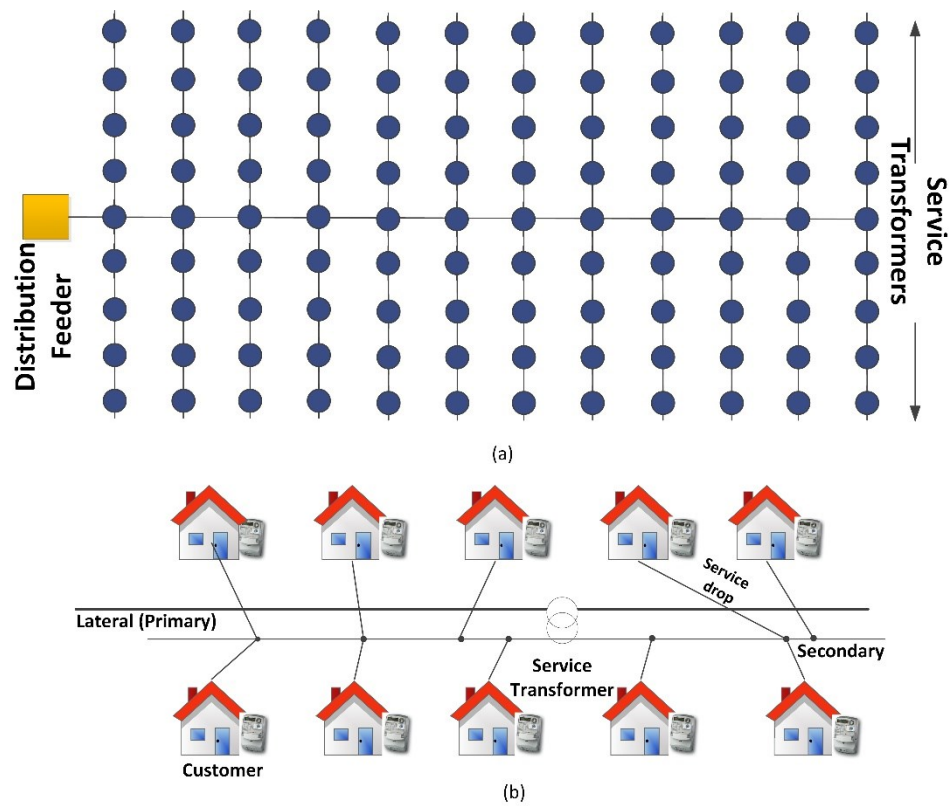


Figure 4.3 Distribution network architecture

(a) Radial configuration of a single distribution feeder with connected services transformers [204] (b) Customers premises services drop connections from the service transformer

4.6. Performance analysis of SDN based SG NAN framework

The proposed communication framework of SDN based WSN for SG NAN was implemented using Castalia [204]. To derive accurate and realistic performance of the model, a popular suburb named Fitzroy from Melbourne, Australia has been considered. It is assumed that all of the houses in this suburb have smart meters installed. The total land area of the selected region in Fitzroy is about

1.28Km² as shown in Figure 4.4. Based on table simulation parameter on the transmission power the whole area has been divided into 96 sectors each covering (100X100 m²). It's found that with a transmit power of 4.5dBm the maximum line of sight distance can reach up to 300m [36]. Based on the observation there are approximately 1000 Smart Meters uniformly distributed within this suburb. Thus, it can be assumed that the average number of smart meters in each sector would be around 10~11. Please note that the traffic profiles of the SG applications are considered based on Table 4.1 The simulation scenario was varied with a different seed value, and total 100 runs were considered to provide results that included average and 95% confidence intervals. The simulation parameters are summarized in Table 4.2

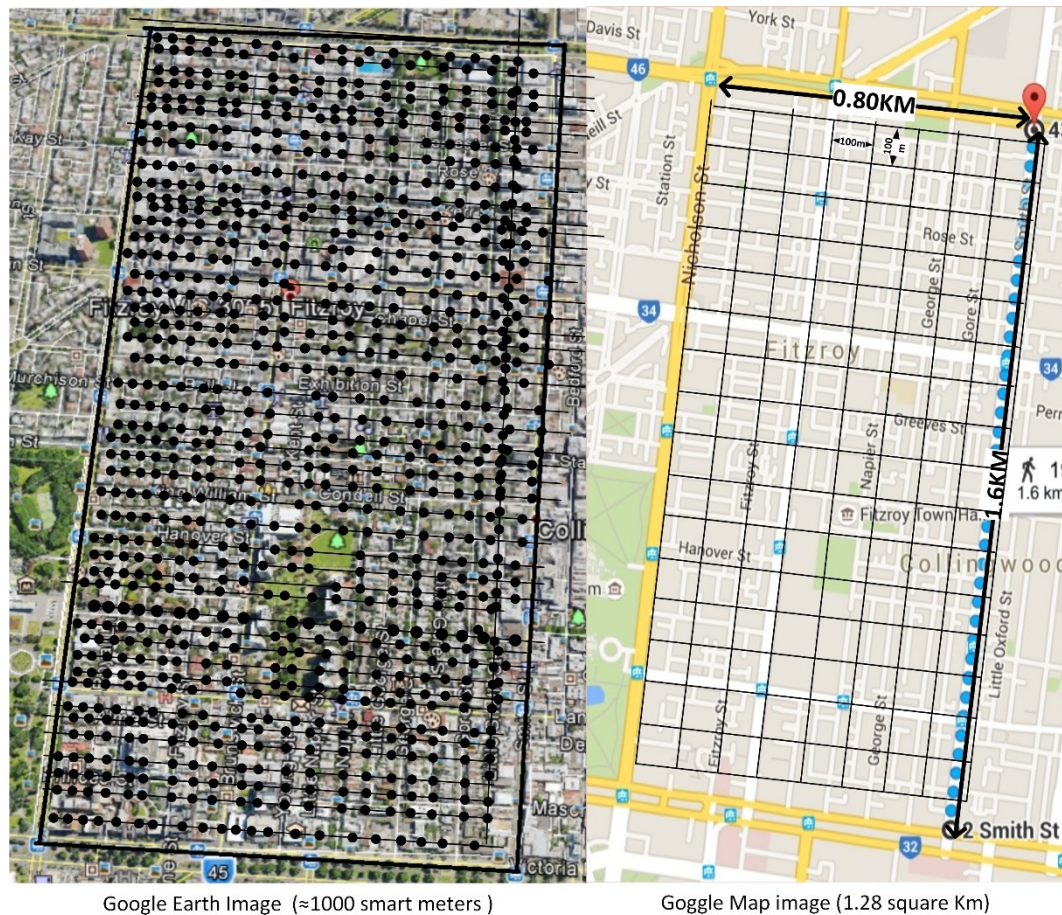


Figure 4.4 Distribution of smart meters in the Fitzroy suburb

Three different simulation scenarios have been developed based on the network configuration. The first scenario only considers predefined flows for all SG applications running in the NAN domain. This network configuration can be regarded as the best-case scenario of the network. Any incoming

packets at the SW will arrive within the flush time out of the defined flows in the flow table. Flush-out time corresponds to a period after which a flow instruction is removed from the flow table due to inactivity of the application. Hence, there will be no delay associated with flow table query. Based on the mentioned SG applications in the table, the network was configured, and an end to end delays have been measured to ensure successful deployment of the proposed framework.

Table 4.2 Simulation settings (SDN based Neighborhood Area Network)

<i>Simulation parameter</i>	<i>Details</i>
Size of simulation area	1600x800 m ²
Number of Smart meters (n)	1000
Radio Range (EN, SNSW, Controller)	~50m [205]
Transmission Power	4.5dBm
One hop distance between switches	200m
Propagation delay	66 μ sec
Storing and forward delay	10ms
Flow resolve rate per controller	100000 [206]
Flow request response time	100 μ sec [206]
Number of clusters	96
Number of considered service transformer	100
Delay requirement- App1(DA)	100ms (Delay sensitive)
Delay requirement- App2 (DR-mission critical)	200ms (Delay sensitive)
Delay requirement-App3 (DR programs)	500ms (Delay tolerant)
Delay requirement-App4 (Outage management)	1s (Delay tolerant)
Delay requirement-App5(Meter reading)	1s (Delay tolerant) [21]

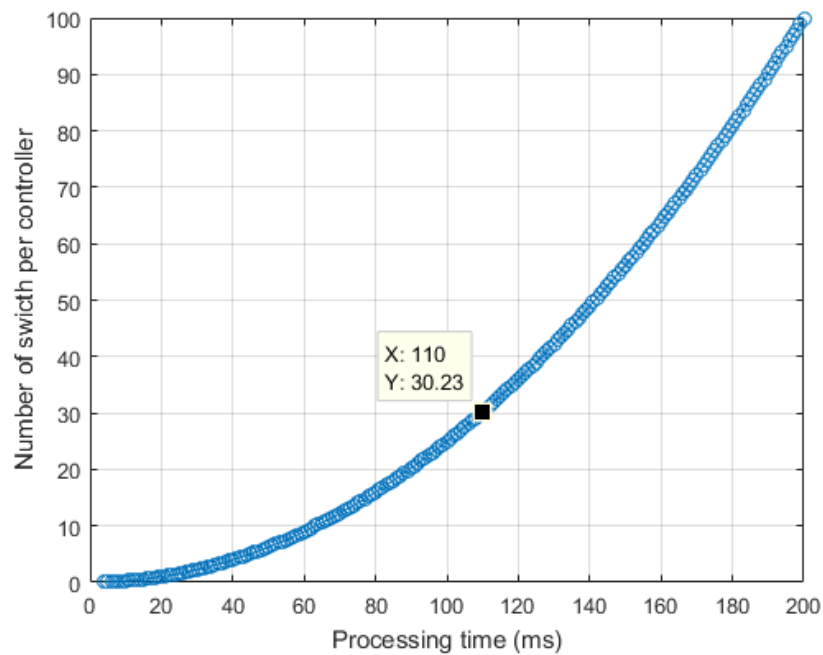


Figure 4.5 Variation of the number of the switch per controller in terms of processing delay

Figure 4.5 shows the relationship between the processing time and a number of the switches per controller based on the derived equation of the optimized number of distributed controllers and switches. Among the actively running SG applications, delay sensitive applications require maintaining strict delay boundary of processing time. Keeping this requirement in mind, the simulation model considered the average delay of 110 ms (average delay requirement of delay sensitive applications) as the minimum required processing time to determine the optimum number of controllers. Based on the analysis, it has been identified that the number of switches that can be handled by a single controller would be about 30. Accordingly, the considered topology of WSN would require four controllers in total if each sector of the NAN is equipped with a single switch. However, the optimal number of controllers is derived based on the proposed mathematical model (presented in Chapter 5), and in a practical scenario, the number may increase due to other factors such as environmental issues, terrain pattern, and placement of the switches at homes.

To evaluate the performance of the proposed model in the worst conditions, the second scenario of the simulation model considers no flows defined for any SG applications. Thus, each time a new application packet arrives at the switch, it is forwarded to the associated controller to get assigned with the new flow type. After successful initialization of flows, the packets are forwarded to the corresponding destinations.

Figure 4.6 shows the average end-to-end delay of different applications during the simulation runtime. The end-to-end delay corresponds to the period taken by a specific packet associated with an individual application traveling from the smart meters/IEDs to the NAN controllers. Further, the best case and worst-case scenario have been compared in terms of average delay. Note that, in the case of best case scenario (Figure 4.6(a)) all SG application had predefined flows stored in the switches whereas in the case of worst case scenario (Figure 4.6(b)) there were no flows stored at any switches in the network. The delay sensitive applications suffer the most in the second case as the overall average delay increases. The increase derived here represents the flow processing time of the network (shown in

Figure 4.6 (c).

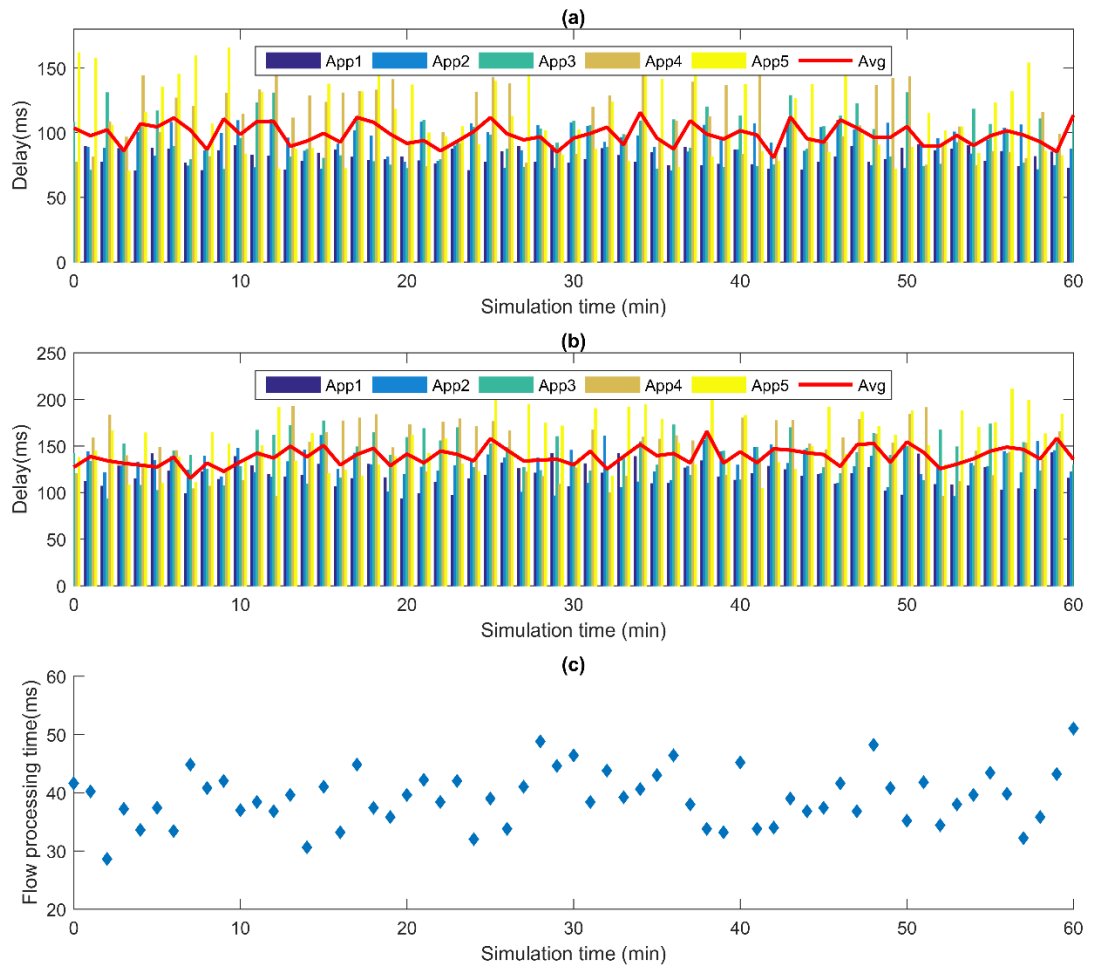
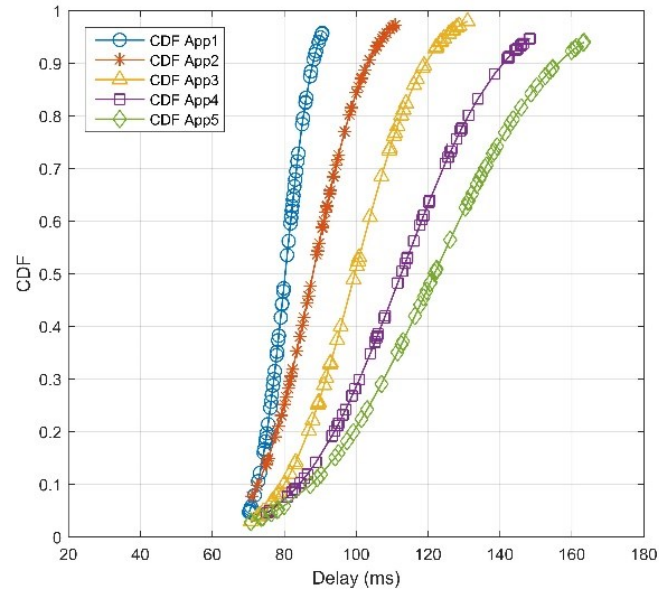
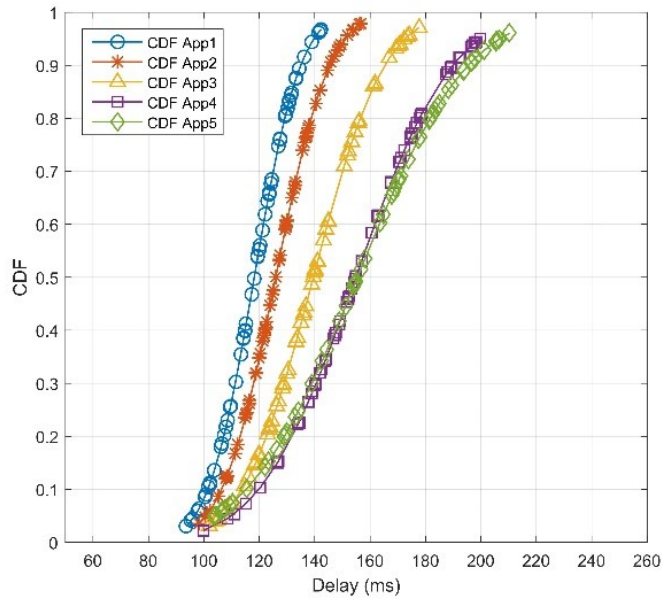


Figure 4.6 (a) Delay profile of different applications and total average delay in the Best-case and Worst-case scenario, and flow processing time



(a)



(b)

Figure 4.7 (a) Packet delivery time taken by different applications in the best-case scenario (b) Packet delivery time taken by different applications in the worst-case scenario

Figure 4.7 (a)-(b) show the packet delivery time and the probability of successful packets delivered within that period for different SG applications in both best and worst case. Cumulative Distribution Function (CDF) graph in Figure 4.7 (a) shows that in the best-case scenario, all packets were delivered to the specified destinations within the delay boundary of the associated applications. In the case of the delay, sensitive applications such as App1 and App2 packets are successful in maintaining strict delay boundary of 100 ms and 200 ms. On the other hand, due to additional flow set up required for

the delay sensitive applications (such as DA (App 1)), in the worst-case scenario (shown in Figure 4.7 (b)), the network fails to deliver delay sensitive packets within the required delay boundary of 100 ms. The additional flow processing time contributes to the increased delays for all of the active SG applications in the worst-case scenario.

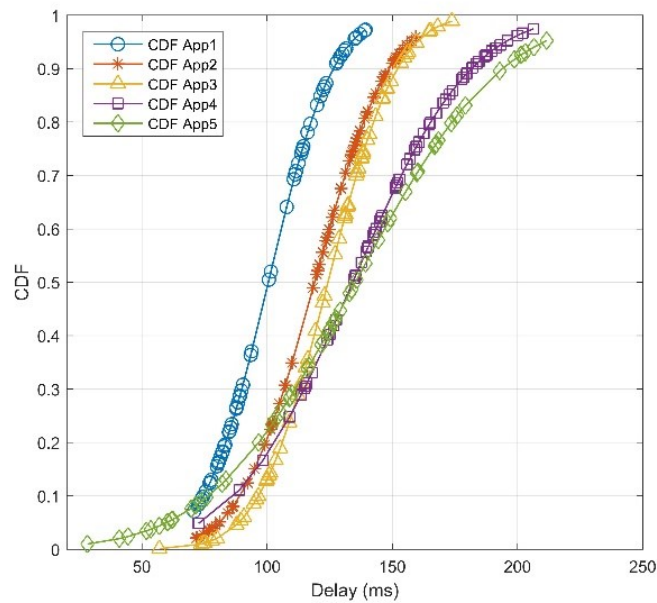
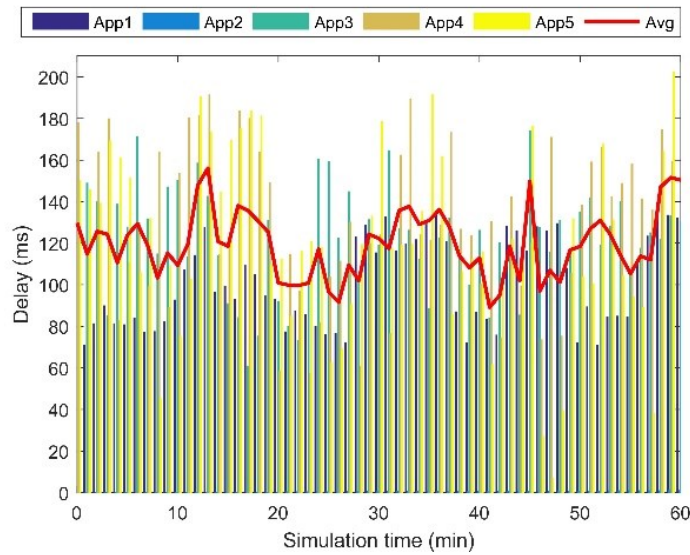


Figure 4.8 (a) Delay profile of different applications in random scenario (b) Packet delivery time taken by different applications in random scenario

The third scenario considers random packet generation from different SG applications. Here, in this

case, predefined flows are assigned to some of the applications (both delay sensitive and delay tolerant). Further, different simulation scenarios were created where the number of predefined applications were varied. The packet generation rate of the different applications is varied by periodicity and stochasticity. As shown in Figure 4.8 (a) and Figure 4.8 (b), it is interesting to notice that if the application is delay sensitive application and the simulation stochastically generates an App1 packet, the network fails to deliver the packet within the required delay boundary. This is due to the placing of a randomly generated packets in the long unresolved buffer queue. Sometimes it also exceeds the flush out time and needs to reassign flow commands each time the SG event triggers. However, a randomly generated delay sensitive application packet needs to be delivered within a strict time limit.

Based on the simulation scenarios discussed earlier, it is evident that it would not be realistic to adopt any of these techniques as there will be some delay sensitive SG applications which require confirmed packet delivery within strict delay boundary. Also, if the applications require flow information every time the packets arrive at the switch, the additional control channel overhead would be overwhelmed with high delay. A simple solution is found in the fourth simulation scenario. The end-to-end delay requirement of delay sensitive SG applications within the NAN usually remains between 25-100 ms, i.e., the DA. Also, mission critical data related to DR has a delay boundary of 200 ms. To handle the identified challenge, two different types of flows named as *pro-active flow* and *reactive flow* have been assigned to handle the delay sensitive and delay tolerant applications respectively. In the case of proactive flows, the SDN controller pushes the flow to the SDN switch right after deploying any delay sensitive application within the network. This reduces the time required to resolve a delay sensitive application packet by avoiding control channel communication between SDN switch and SDN controller. On the other hand, reactive flows are unicast only to the corresponding SDN switch on demand basis. It is to be noted that the proactive flows are permanent in contrast to the reactive flows.

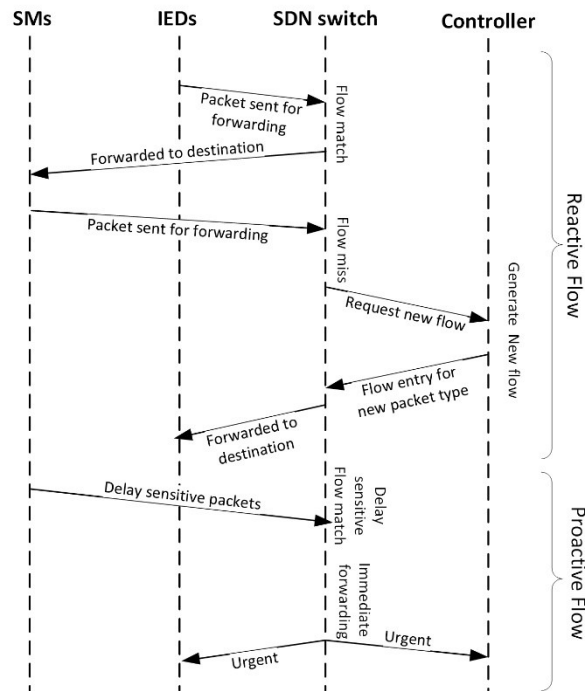
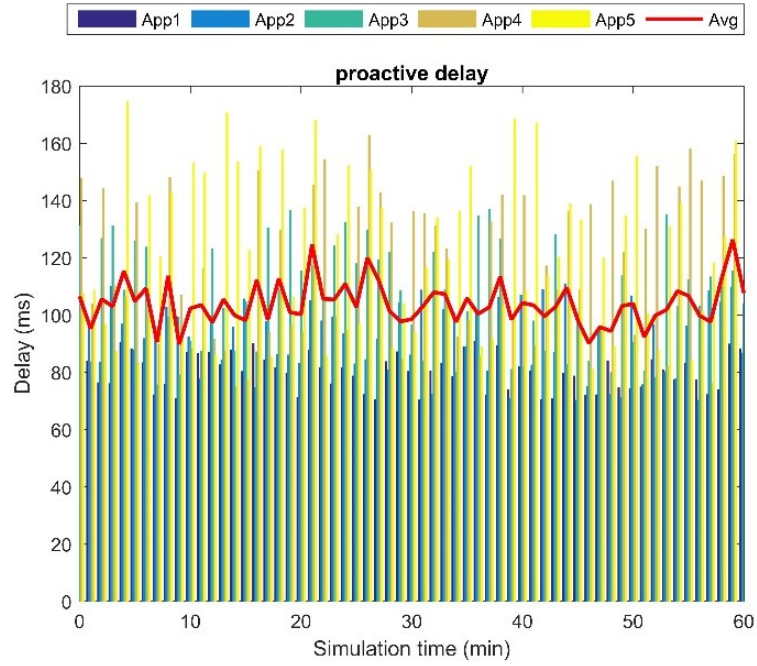
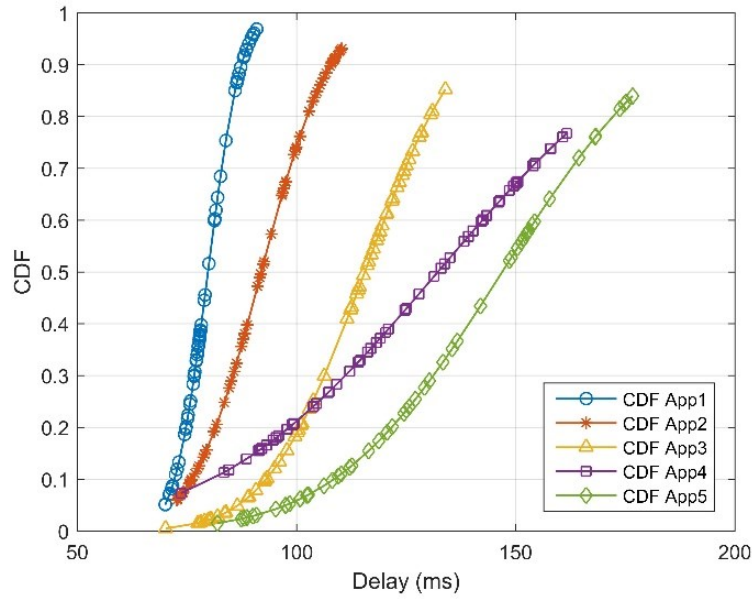


Figure 4.9 Message exchange between the network devices based on reactive and proactive flow types

In the case of the delay sensitive applications, whenever a packet arrives at the switch it's being broadcast to the associated switches based on the predefined proactive flow command. In this framework, proactive flow command is used to handle all the delay sensitive SG applications. On the other hand, upon receiving an application packet for the first time at the switch, the controller pushes a reactive flow into the switch to handle the packet. After getting assigned to a particular reactive flow command, similar application packets could be forwarded in a manner. Furthermore, for any delay sensitive application, packets are broadcasted to all the switches with infinite flush out time. In the case of a proactive flow the controller pushes flow instruction to the switches immediately after deploying a new application whereas, in the case of reactive flow, the controller replies only after receiving a control packet requesting flows sent by the switch. Figure 4.9 shows the handshaking messages between the network devices based on reactive and proactive flow types.



(a)



(b)

Figure 4.10 (a) Delay profile of different applications in case of proactive and reactive flows (b) Packet delivery time taken by different applications in case of proactive and reactive flows

Figure 4.10 (a) shows the delay profile of considered applications while implementing proactive and reactive flows. It can be observed that the average total delay for all the active application is around 106 ms. Here, the delay sensitive applications were assigned with proactive flows and their delay requirement is served successfully. On the other hand, with reactive flows the delay tolerant applications also successfully met the delay requirement. Figure 4.10 (b) shows the probability of

packet delivery in terms of delay for different applications. It can be observed from the CDF graph (Figure 4.10 (b)) that the proposed proactive and reactive flows could successfully handle all active SG applications considered in this simulation model.

4.7. Summary

The chapter presents a detail network work architecture of the SDN based NAN. Development of the communication framework included appropriate communication system model, traffic modeling, distribution grid architecture mapping against SDN based NAN architecture. Practical WSN in a SG network will be deployed randomly as there can be various types of network topologies. Accurate and realistic performance analysis will depend on large data set simulations, the number of summation runs and variation in the simulation parameters. In this context, the statistical study provides more authenticity to the simulation results as it uses numerical values and cross checks them. A range of simulation scenarios were developed using the Castalia Simulator to model both delay sensitive and delay tolerant SG applications using the proposed SDN based WSN communication framework. Simulation scenarios considered four different flow command handling mechanisms to demonstrate the performance analysis. Among them, the scenario with the pro-active flow command shows efficient handling of both delay sensitive and delay tolerant applications. The number of distributed controllers was initially derived based on the minimum required processing time of the delay sensitive application. However, it has been identified that there is a need to determine the optimized number of distributed controllers in the NAN domain for maximizing the efficiency of the communication framework. The issue is further investigated and smart solution is derived and presented in the next chapter.

CHAPTER 5. Optimization of Distributed Controllers and Development of SDN based SG NAN Applications

5.1. Overview

Chapter 5 provides a description of the contributions that address research question 3. The SDN based NAN architecture would need to accommodate large data sets derived from the sensor devices installed in the customer premises. The proposed SDN based NAN communication framework in Chapter 4 characterizes different application traffic via the application classifier in the switch and in case of a failure to classify the application, the switch corresponds with the SDN controller to retrieve a flow command. Due to having a large operational region, a NAN would require multiple distributed controllers to support all of the deployed SG applications within the distribution domain. Also, satisfying the delay requirement of the event triggered or delay sensitive SG application would largely depend upon the time taken to assign flow commands for all of the running applications (both delay tolerant and sensitive SG applications) at any instance. Pro-active flow commands would be beneficial in this case, as predefined flows will be stored in the switch flow tables and controllers would require less time to assign flow commands to newly arrived application traffic. Efficient load balancing and the ability to fulfill the requirements of the delay sensitive SG applications necessitates multiple distributed controllers for the NAN domain. Selecting a random number of distributed controllers could result in a waste of communication resources. Whereas, it is immensely important to determine the optimum number of distributed controllers that would satisfy the communication requirements as well as provide maximum efficiency while supporting delay sensitive applications. To increase the capacity of the network a novel mathematical framework has been presented that derives the optimal number of deployed controllers within an SDN-based NAN. The results derived from the analytical model are further used to find novel techniques to develop SDN-based SG applications such as G2V and AMI applications. Firstly, the SDN based G2V load management system is developed to support

valley filling service during off peak hours. Novel communication network architecture and traffic model is presented in conjunction with a smart prediction algorithm to support the G2V application in SDN NAN. Secondly, performance analysis of AMI applications in an SDWSN based NAN is presented by developing extensive simulation scenarios. Both periodic and event triggered applications were considered. At the same time, the AMI applications considered varied in terms of delay requirements. The simulation outcomes were analyzed and presented to validate the proposed SDWSN based NAN communication framework operating with optimized number of distributed controllers. The proposed methods yield tangible effects on the overall performance of the SG network while addressing research question number 3. In the end, the statistical analysis techniques are also repeated for verification.

5.2. Proposed Mathematical model

Let's assume, α is the total processing time of a single controller to resolve an incoming flow request and to disseminate the traffic to the appropriate destination. The total processing time depends on three parameters: (a) flow request delay, (b) associated communication delay, and (c) flow request-response delay. Flow request delay is the period consumed by the switch whilst identifying that flow instructions are not in the flow table for a new flow and sending the flow information to the controller. The communication delay is a summation of the switch store and forwarding delay and the propagation delay. Lastly, the flow request response time is consumed as the controller processes the flow information for the incoming flow instruction request packets. This can be written as:

$$\alpha = \alpha_{FR} + \alpha_{FRR} + \alpha_{CD1} + \alpha_{CD2} \quad (5.1)$$

Where, α_{FR} , α_{FRR} , α_{CD1} and α_{CD2} represents flow request delay, flow request response time, communication delay from switch to controller, and controller to switch, respectively.

Considering,

$$\alpha_{CD1} \cong \alpha_{CD2} \cong \alpha_{CD} \quad (5.2)$$

Thus,

$$\alpha = \alpha_{FR} + \alpha_{FRR} + 2 \alpha_{CD} \quad (5.3)$$

Now, assume α_{PD} is the propagation delay and α_{SF} is the store and forwarding delay of the switches. The storing and forwarding delay is the time period taken by the switch to place the packet into the queue of the transmission buffer and to transmit the packet at the earliest opportunity. Thus, the total communication delay can be represented as

$$\alpha_{CD} = \alpha_{PD} + \alpha_{SF} \quad (5.4)$$

If there are h number of hops between a switch and a controller then,

$$\Delta_{PD} = \sum_{i=1}^h \alpha_{PD_i} \quad (5.5)$$

$$\Delta_{SF} = \sum_{i=1}^h \alpha_{SF_i} \quad (5.6)$$

Therefore (5.4) can be re-written as

$$\alpha_{CD} = \sum_{i=1}^h (\alpha_{PD_i} + \alpha_{SF_i}) \quad (5.7)$$

For, simplification let's consider $\alpha_{PD_i} \cong \alpha_{PD_{i+1}} \cong \dots \cong \alpha_{PD_{i+h}} \cong \alpha_{PD}$ and $\alpha_{SF_i} \cong \alpha_{SF_{i+1}} \cong \dots \cong \alpha_{SF_{i+h}} \cong \alpha_{SF}$. Therefore, (5.7) can be expressed as

$$\alpha_{CD} = (\alpha_{PD} + \alpha_{SF}) * h \quad (5.8)$$

To determine the value of α_{FRR} in the (5.3) let's consider, ξ is the flow resolve rate per controller and η is the number of switch assigned per controller. Then, the α_{FRR} can be written as

$$\alpha_{FRR} = \frac{\eta \beta}{\xi} \quad (5.9)$$

Now, by replacing equation (5.8) and (5.9) in (5.3)

$$\alpha = \alpha_{FR} + \frac{\eta \beta}{\xi} + 2(\alpha_{PD} + \alpha_{SF}) * h \quad (5.10)$$

Hence,

$$\eta = \frac{[\alpha - \alpha_{FR} - 2(\alpha_{PD} + \alpha_{SF})h]\xi}{\beta} \quad (5.11)$$

For inter sector communication, sector based distance (SBD) routing protocol (cf. section II in [207]) has been considered. According to SBD, switches continue forwarding their flow request to their immediate neighbor switch, which lies on the same row in the virtual grid until the packet reaches the switch that is on the same column as the controller. The flow request will then be forwarded vertically up or down until it reaches the controller. Figure 5.1 shows the routing of packets from switch to the controller with SBD routing protocol.

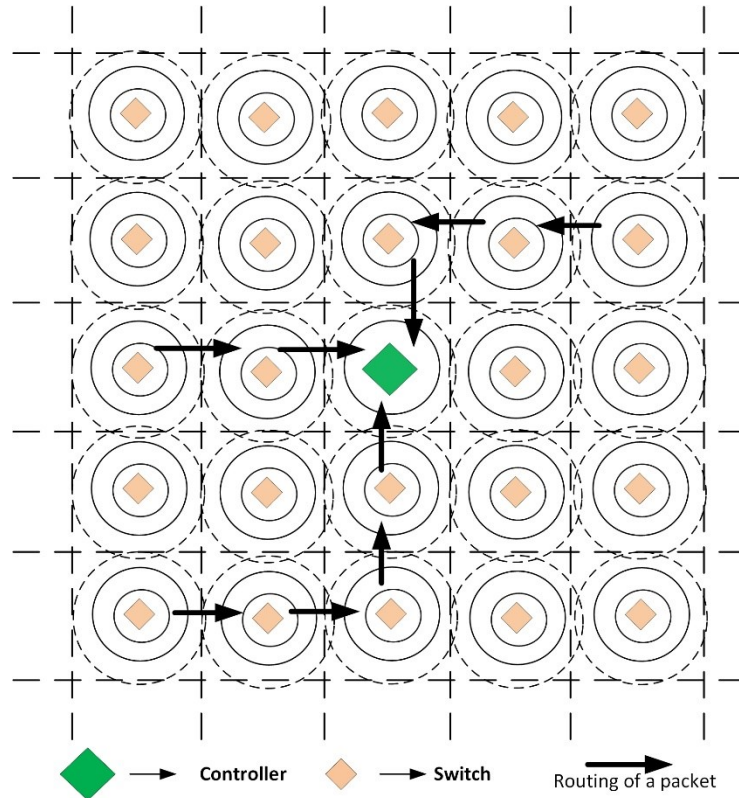


Figure 5.1 Routing of packets from the switch to controller based on SBD

Lemma 5.1:

Let, there are η number of switches uniformly distributed in a $(\sqrt{\eta} \times \sqrt{\eta})$ grid with one switch each cell as shown in Figure 5.2. A controller is deployed in the middle of the grid and all η switches are assigned to this controller. Then, the average number of hops 'h' from a switch to controller is $\sqrt{\eta}/2$ (approximately)

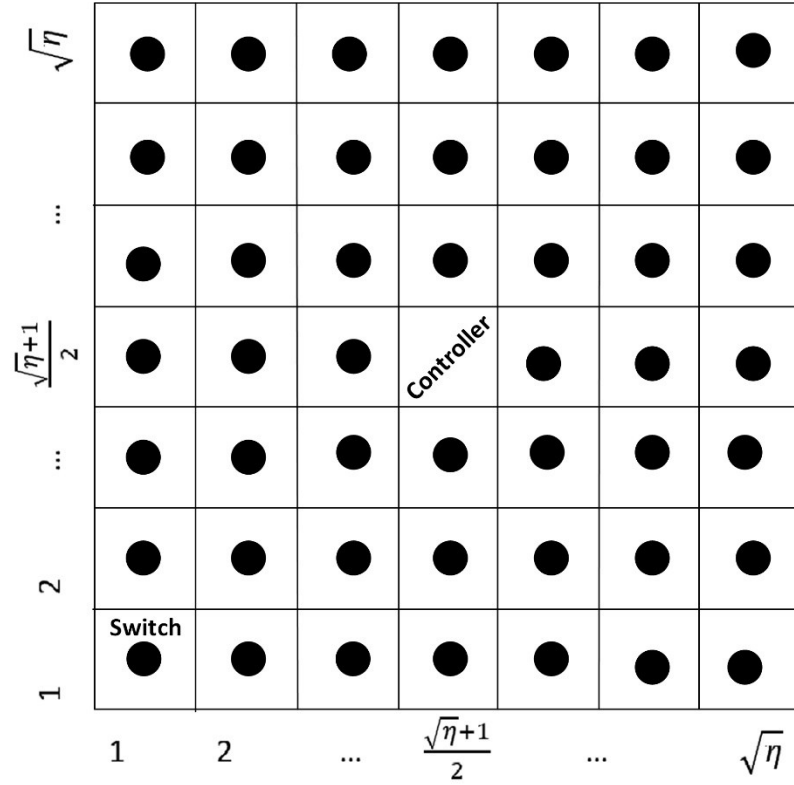


Figure 5.2 Hop counts in a virtual grid

So, (5.11) can be rewritten as (proof of Lemma 5.1 is shown in Appendix A)

$$\eta = \frac{[\alpha - \alpha_{FR} - (\alpha_{PD} + \alpha_{SF})\sqrt{\eta}]\xi}{\beta} \quad (5.12)$$

We can write (5.12) into a binomial quadratic equation, i.e.,

$$\eta\beta + \sqrt{\eta}(\alpha_{PD} + \alpha_{SF})\xi + (\alpha_{FR} - \alpha)\xi = 0 \quad (5.13)$$

The solution of (5.10) will derive the minimum number of switches under a single controller within the NAN. Hence, the number of switches per controller would be

$$\eta = \left\{ \frac{-(\alpha_{PD} + \alpha_{SF})\xi + \sqrt{((\alpha_{PD} + \alpha_{SF})^2 \xi^2) - 4\beta(\alpha_{FR} - \alpha)\xi}}{2\beta} \right\}^2 \quad (5.14)$$

Here, β will depend on the number of smart meters within the NAN. To determine the optimal number of switches of the NAN let's assume, λ is the packet arrival rate (per sec) at the switch, m is the number of smart meters under each switch, and p is the packet generation rate per second at each of the smart meters.

$$\lambda = m * p \quad (5.15)$$

If a switch S_w can handle ε number of packets per second and the total number of smart meters in a NAN is M , the outcome of the following convex optimization problem would derive the optimal number of switches required in the network

$$\begin{aligned} & \text{Minimize } S_w = \frac{M}{m} \\ & \text{s.t. } m \leq \varepsilon/p \end{aligned} \quad (5.16)$$

Now, the optimal number of controller C_t would be

$$C_t = \frac{S_w}{\eta} \quad (5.17)$$

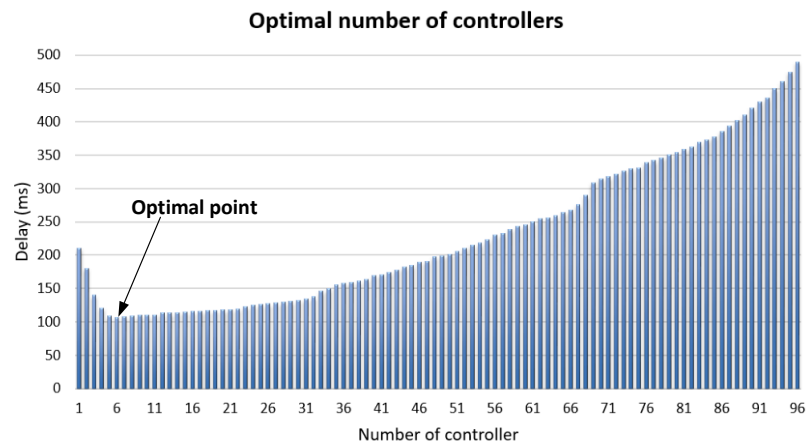


Figure 5.3 Optimal number of deployed controllers

To determine the actual optimal point, simulation scenarios were developed by varying the total number of deployed controllers. Figure 5.3 shows the required number of controllers and associated average delay statistics while varying number of controllers in the simulation scenario (worst-case). Considered SG applications in this study represented maximum delay in the worst-case scenario and the optimal point here could handle the corresponding delay without implementing the proactive flow. The outcome reveals that the optimal point is reached when the number of controllers is 6, and the average delay was at the minimum value (106 ms). Thus, based on the simulation outcome, it is evident that the proposed mathematical model derived a near realistic estimation (comparing with Figure 4.5 in Section 4.6) of an optimal number of required controllers.

5.3. Performance analysis of AMI applications in the SDN based NAN

Most of the SG based AMI applications including PEV, AMR, and DR require two-way

communication between the devices and the utility control centers. The main objectives of these applications are to ensure efficient energy consumption and optimal utilization of energy resources via customer participation. An SDN based NAN using WSN should support a large number of M2M devices. The M2M devices installed at the NAN domain collect measurements from residential or commercial buildings and send the information to a DAP using frequent low data rate transmissions. As a result, the medium access channel could become overwhelmed with too many access requests. For example, in the event of outage, all the M2M devices could try to send an event report simultaneously which could increase the network access load exponentially and lead to network failure.

To this context, an SDWSN based NAN simulation model was developed in Castalia v3.2 [173]. It was assumed that the smart meters installed at the premises operate using the CC2530 specification, which supports the IEEE 802.15.4 Zigbee protocol operating on the 2.4 GHz band. Two simulations were conducted with the AMI application characteristics in the NAN domain. First, a generic SDN based AMI application was considered where small data bursts (100 bytes) are sent from the smart meters to the Utility control center. The data burst transmission intensity followed an exponential distribution. Further, the reporting cycle was varied from 1 min to 5 min. A total number of 1200 smart meters were considered where 120 SDN switches were uniformly distributed. It's assumed that delay sensitive applications like PEV charging/discharging and DR are also accommodated in the reporting interval. Next, the effect of the traffic loads on the proposed SDN based NAN was observed.

In the second simulation scenario, a power outage event was considered. It was assumed that a group of smart meters would transmit the 'last gasp' message asynchronously within an interval of 10 sec. The number of affected smart meters was varied between 400 to 1200 with a step of 100 and effects analyzed to evaluate the SDN based NAN. As the 'last gasp' message is a type of delay sensitive SG application, the flows were predefined via the SDN controller and stored in the associated switches. The flush out time for this application packet was set to infinity due to random generation nature of

the packets. Moreover, any predefined delay sensitive application packets are placed into a priority queue for immediate forwarding.

Results from the first simulation trial are presented in Figure 5.4 and the average end-to-end delay of both delay tolerant and delay sensitive applications are plotted against the reporting interval. The end-to-end delay increases as the reporting interval decreases, which is due to the high number of smart meters trying to deliver the packets within a shorter period of the switch as it attempts to forward the packets to the destination. However, with a reporting interval of 1 min, the proposed model successfully delivered the delay tolerant packets with a 97% success rate, as shown in Figure 5.5. The delay boundary for most of the delay sensitive applications varies between 70-100 msec [8]. The proposed network model supports all of the major delay sensitive SG applications and successfully disseminates the packets within a strict delay boundary. As shown in Figure 5.5, the success rate is 100% for all types of application packets when the reporting interval is equal to or greater than 3 min.

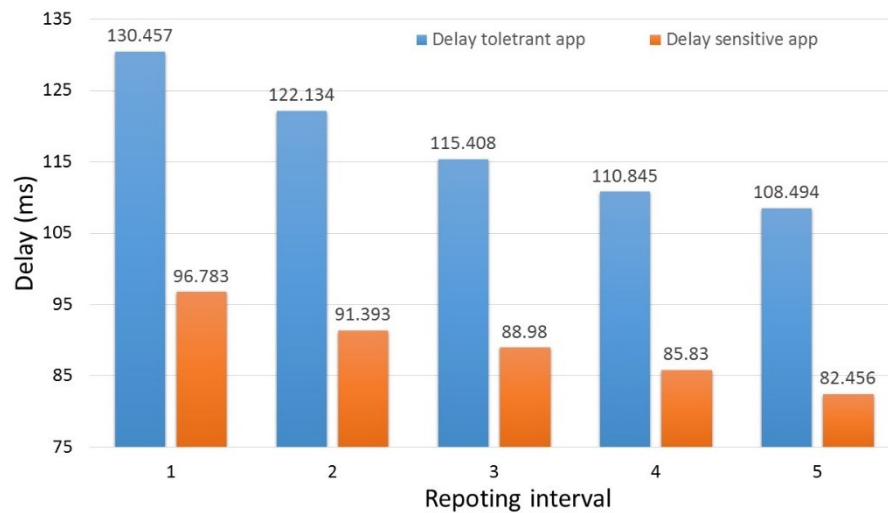


Figure 5.4 Average delay of AMI traffic in SDN based NAN

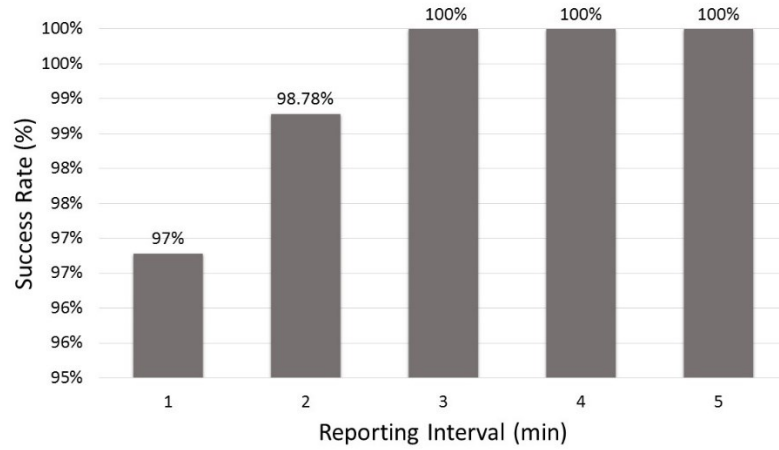


Figure 5.5 Success rate of AMI traffic in SDN based NAN

The second simulation results show the success rate and associated end-to-end packet delay of the ‘last gasp’ messages against a varying number of affected smart meters. Figure 5.6 shows the uplink delay of AMI traffic in the proposed SDN network. Results show that the SDN based NAN could provide support for 900 affected smart meters with 100% success rate. The success rate starts to fall as more affected smart meters try to send the ‘last gasp’ message within a small interval of 10 sec. The smart meters are supposed to run on their capacitive power after the outage event and transmit the packet with the remaining capacitive power. Based on the outcome derived from the second simulation it is evident that the proposed model can successfully deliver the outage event messages within the required delay boundary. However, successful reception of outage alarms reduces the number of smart meters increase. Accordingly, the end-to-end delay for outage alarm delivery gets higher as more smart meters get installed on the network. Based on the simulation statistics it would be interesting to develop an analytical model to derive the maximum number of smart meters operating with a 100% success rate while delivering an outage alarm. To keep the focus of the simulation model limited, this issue is left as a future research interest.

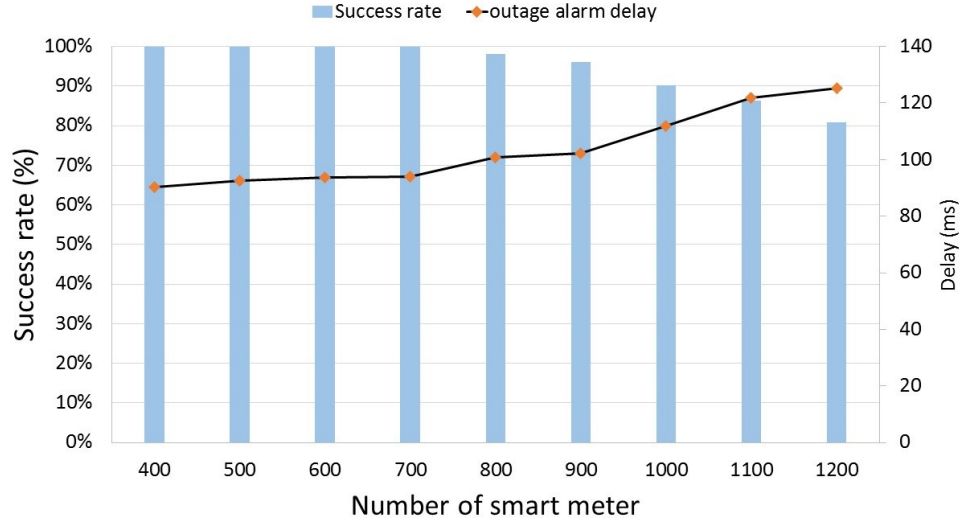


Figure 5.6 Uplink delay of AMI traffic in SDN based NAN

5.4. SDN based Application specific traffic modeling: G2V

The proposed G2V smart load scheduling and management scheme utilizes an efficient optimization scheme to estimate the off-peak time slots of the daily load curve. The novel communication network architecture exploits SDWSN principles to facilitate smooth dissemination of energy and control information while facilitating the rapid dissemination through the network of new and updated services. The stochastic nature of burst generation within a particular time slot permits group based charging with differentiated charging rates. The traffic generated can be evenly distributed so that the uplink channel is not congested. The group wise charging method reduces overall network load at the controller as only a limited number of charging stations communicate with the controller at any instance. Hence, the overall scheme is highly reliable and scalable in term of communication overhead and can be deployed along with a multiple application running in the SG NAN background.

5.4.1. Proposed G2V load management scheme

This section provides a description of the proposed G2V load management scheme including the architecture and communications model.

5.4.1.1. Conceptual Architecture of SDN based G2V

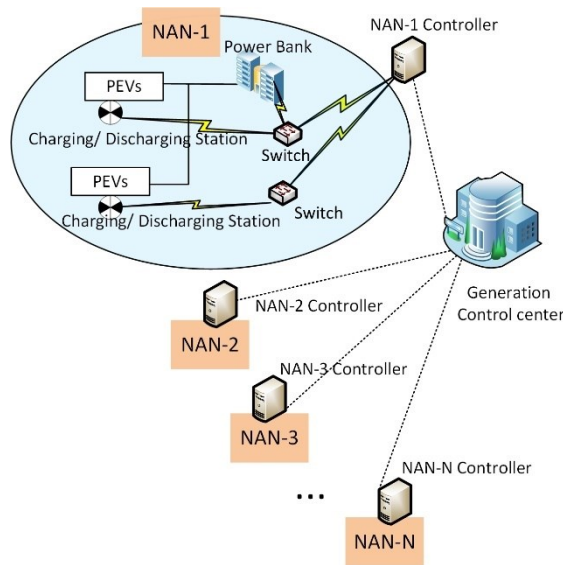


Figure 5.7 Conceptual architecture of proposed SDWSN based NAN

Figure 5.7 shows the conceptual network architecture of the proposed G2V load scheduling and management scheme. The PEVs are assumed to be parked at the home premises where they connect to the charging/discharging stations via a power outlet. The charging/discharging stations are connected to a power bank, and the number of power banks needed for a particular number of dwellings in a NAN will depend on the capacity and number of batteries installed at the power bank. The power bank can provide power to the grid when required. During peak periods, the grid requires additional units of power to satisfy demand so it would be financially beneficial for the grid authority to draw power from the power banks rather than starting up additional generation units. Power banks can store energy along with the attached PEVs by using the valley filling technique. Also, power banks can store energy from other NAN associated renewable energy sources. Management of the power banks and decisions about utilizing power from the power banks is carried out in generation control centers.

Based on the proposed model, PEVs are assumed to be connected to the power outlet while they are parked at the home premises. The vehicle charging session would initiate autonomously during off peak periods, and the length of the session is determined based on the SoC level of the vehicle battery. By utilizing intelligent statistical multiplexing, the NAN controller would evaluate the optimum period for the charging session and number of vehicles that could be charged during that session. The

controller evenly distributes the charging probability among the contending PEVs. The proposed energy scheduling algorithm receives crucial decision parameters via the novel SDWSN. The control plane consists a NAN controller, which is connected to the generation control center. The power banks, PEVs and charging/discharging stations connect to the data plane of the SDWSN network. The novel G2V application operates in the NAN controller which is responsible for generating possible route plans or flow commands and transmits the flow information to the network switches.

5.4.1.2. Communication model

Whenever the PEVs connect to the power outlet, the On-Board Unit (OBU) installed in the vehicle sends a unicast message to the charging station with battery information such as SoC, rated capacity and other information as required. The charging station replies with an authorization request message and PEVs send an authorization response message to complete the registration process. The NAN controller transmits possible charging window information to the charging station and the charging station updates the queued vehicles and periodically sends this information to the NAN controller. Based on a linear prediction algorithm a NAN controller estimates total energy required on a single day by all of the PEVs. The estimation is sent to the generation control center to compare with the off-peak period demand curve. If the required power can be accommodated within the current generation capacity, a control message is sent to the NAN controller to initiate a charging session at the start of the off-peak period.

The charging station sends an energy allocation request to the switch, and if a predefined flow is available to initiate charging, the switch replies with the energy allocation slot information. Upon receiving the information, the charging station starts the energy allocation. Figure 5.8 shows the traffic exchange model of the proposed system.

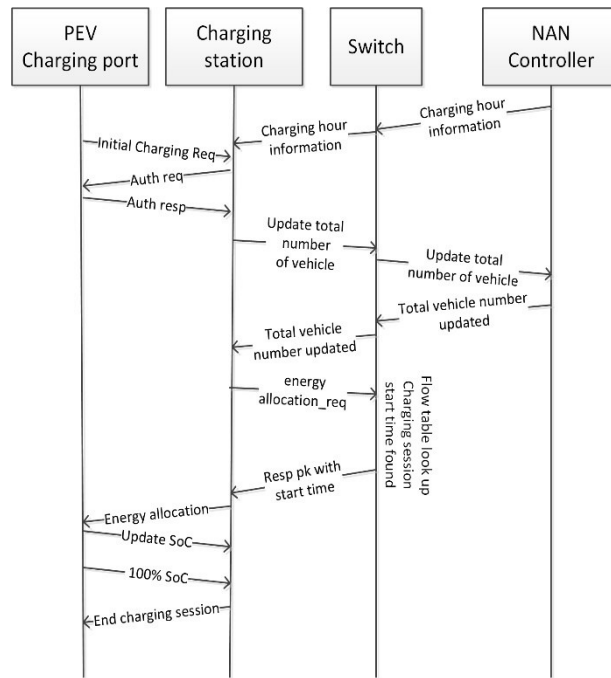


Figure 5.8 Traffic exchange model

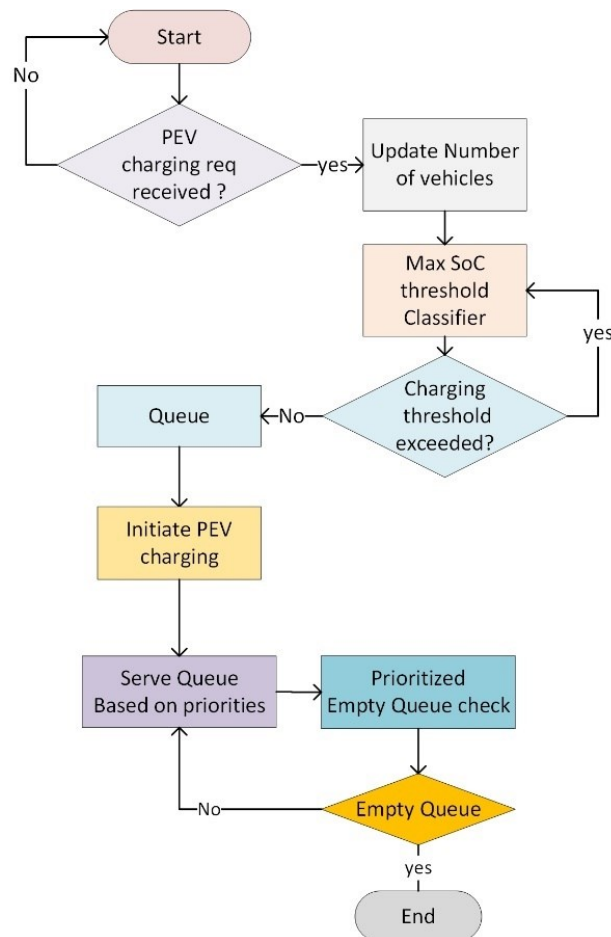


Figure 5.9 Flow chart of PEV charging algorithm

Figure 5.9 Shows the PEV charging algorithm implemented at the charging stations. After registering the contending vehicles, the charging station intelligently groups the PEVs and generates PEV queues

based on the SoC threshold level determined by the proposed energy scheduling algorithm (explained later in this section). To balance and regulate the demand-supply curve from the generation, it's important to estimate the exact power required by a NAN during PEV charging hours in a suburb. A linear prediction model [177] [178] is used to the NAN controllers to predict the PEV charging demand for the next day based on the real-time load information.

During the EV charging window if demand from n PEVs at time slot t is $\Delta(t)$, then the total demand will be

$$\mathfrak{D}_n = \sum_{t=1}^L \Delta_n(t) \lambda \quad (5.18)$$

Where, L is the number of time slots over the 24 hours, each with length λ . If the current time is t and we want to estimate the demand at $(t+T)$, the real-time demand information $\{\Delta_j^k\}_{k=t-N+1}^t$, at t can be used to approximate the value of P_j^{t+1} at time $(t+1)$ using the LP model used in (Appendix B) [186].

Now assume, at the time $(t+T)$, the PEV charging session will start, and the power generation is required to meet the daily PEV charging demand. Let us assume; the total required power ε_m^{t+T} for the PEV charging session by individual NANs is

$$\varepsilon_m^{t+T} = \varepsilon_1^{t+T} + \varepsilon_2^{t+T} + \dots + \varepsilon_m^{t+T} \quad (5.19)$$

If, at time $(t+T)$, the generation capacity is C_{t+T} and the supply is S_{t+T} then we have to minimize the difference between the supply and peak demand of P_{t+T} . Thus, the minimization problem can be expressed as:

$$\min \left(\sum_{t+T}^{L_p} P_{t+T} - S_{t+T} \right) \quad (5.20)$$

Here, L_p is the time slot during the charging period

Subject to:

$$S_{t+T} = C_{t+T} + \varepsilon_m^{t+T} \quad (5.21)$$

And,

$$S_{t+T} \geq \frac{g_n^{t+T}}{\lambda} \quad (5.22)$$

Where, g_n^{t+T} is the demand of n PEVs during charging hours. Based on the demand information aggregated from all of the NANs, the generation controller allocates power for each NAN using Jain's fairness index [208] so that the NANs do not have to suffer power shortages during EV charging sessions. The Jain fairness index is explained by

$$i_{q_n}^{t+T} = \frac{(\sum_{l=1}^M g_n^{t+T})^2}{M \cdot \sum_{l=1}^M g_n^{t+T^2}} \quad (5.23)$$

Where, $i_{q_n}^{t+T}$ is the fairness index. The value of $i_{q_n}^{t+T}$ will vary between $1/n$ to 1. If the generation supply capacity for PEVs charging is C_{t+T} , then, allocated energy for n^{th} NAN at $(t+T)$ would be

$$\tau_n^{t+T} = (i_{q_n}^{t+T}) * C_{t+T} \quad (5.24)$$

Now, the allocated energy would be available to the PEVs once they connect to the charging stations. To maintain fairness among the charging vehicles, a charging threshold level is periodically updated based on the number of the connected PEVs. If the number of the PEVs is W , then the charging threshold η for each PEV is

$$\eta = \frac{\tau_n^{t+T}}{W} \quad (5.25)$$

Thus, during each period of updating the threshold if the battery size is 16kWh with a rated capacity of 80%, the maximum SoC should be

$$SoC(\%) \leq \frac{\eta \cdot \Delta_t}{(1 - \Delta_i) * S_i * \frac{\varepsilon}{\gamma}} \quad (5.26)$$

Δ_t is the time period for updating the threshold, Δ_i is the initial SoC, S is the battery size, ε is the battery rating and γ is the charging efficiency. The total energy requirement for charging a given EV fleet becomes

$$E_{total} = \sum_{i=1}^K (1 - \Delta_i) * S_i * \frac{\varepsilon}{\gamma} \quad (5.27)$$

5.4.2. Performance analysis of SDN based G2V

A Castalia v3.2 [173] based simulation model was developed to evaluate the performance of an SDN based G2V load management system. A PEV charging window from 6 pm to 7 am was considered. It's assumed that PEVs from five NANs will return home between this charging window and get plugged in for charging. It's also assumed that each NAN has 400 houses with one smart meter connection and one charging station at each of the premises. It's assumed that all of the EVs have the same battery size of 16 kWh with a rated capacity of 80% and the initial SoC level of the batteries is uniformly distributed within the boundary range of 0-50%. The charging stations have an energy transfer efficiency of 90%. It's also assumed that the maximum charging rate is 3.6 kW using a regular 240V/15A power outlet. Please note that to avoid complexity in the simulation model, no voltage drops and losses were considered. It is further assumed that the EV batteries are following a linear charging profile. Based on the statistical data extracted from the AEMO website [187], with the proposed model, 100% of this power can be drawn if there are approximately 1600 PEVs. Table 5.1 shows the simulation parameters and corresponding settings.

Table 5.1 Simulation Parameters of SDN based G2V

<i>Parameter</i>	<i>Setting</i>
Transmission Power	4.5 dBm
Data Rate	250 Kbps
Modulation Type	PSK
Bits Per Symbol	5
Bandwidth	5 MHz
MAC Protocol	Std MAC 802.15.4
Number of NAN	5
Number of charging station in a NAN	1600
Total number of Number of PEVs	1600
Max Grid capacity	6150KWh
Number of SDN switch	160
Charging Staion (CS) to Switch communication	12packets per hour (pph)
Switch to Controller communication	12pph

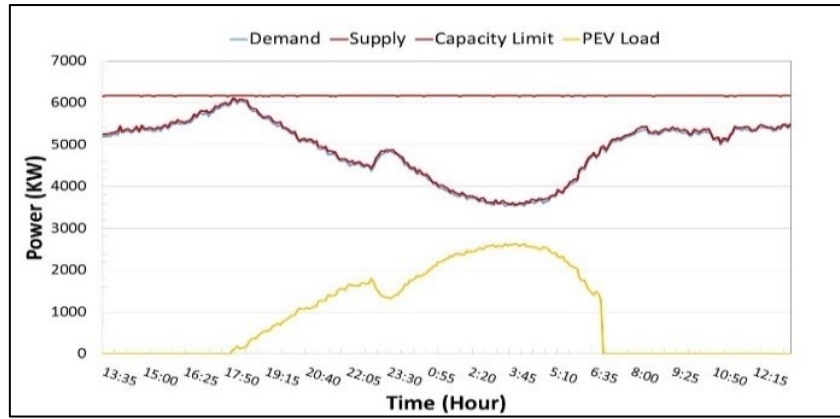


Figure 5.10 Grid capacity, demand, power supply and PEV load profile

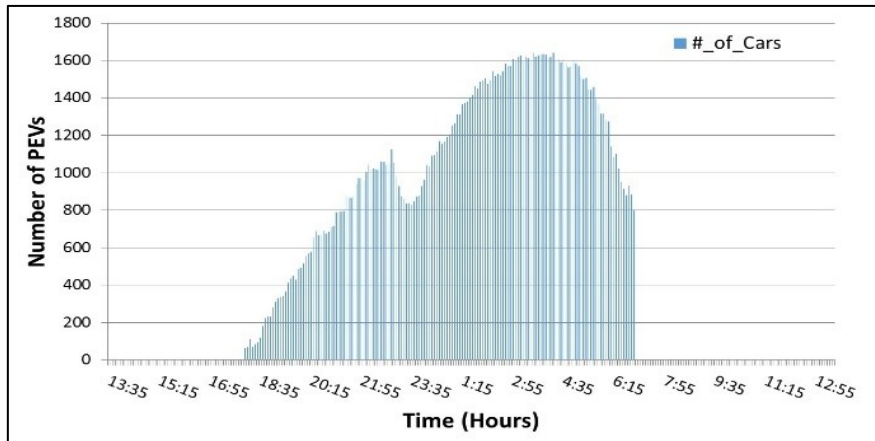


Figure 5.11 Total number of PEVs during charging session

Figure 5.10 shows the total PEV load during a charging session for five NANs. The maximum grid capacity is approximately 6000 kW. The proposed G2V load management valley fills the gap during the off-peak hours between 6 pm and 7 am. Figure 5.11 shows the total number of the PEVs that can be accommodated throughout the charging session. The total amount of power required for PEV charging is divided amongst the contending NANs based on Jain's fairness index [208]. As the charging hour started, PEVs started to join the network from the participating NANs.

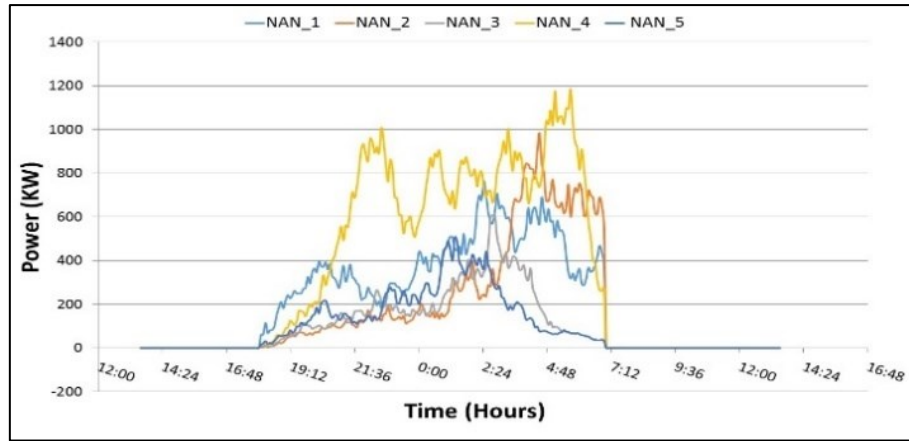


Figure 5.12 Total energy allocation for each NAN based on fairness index

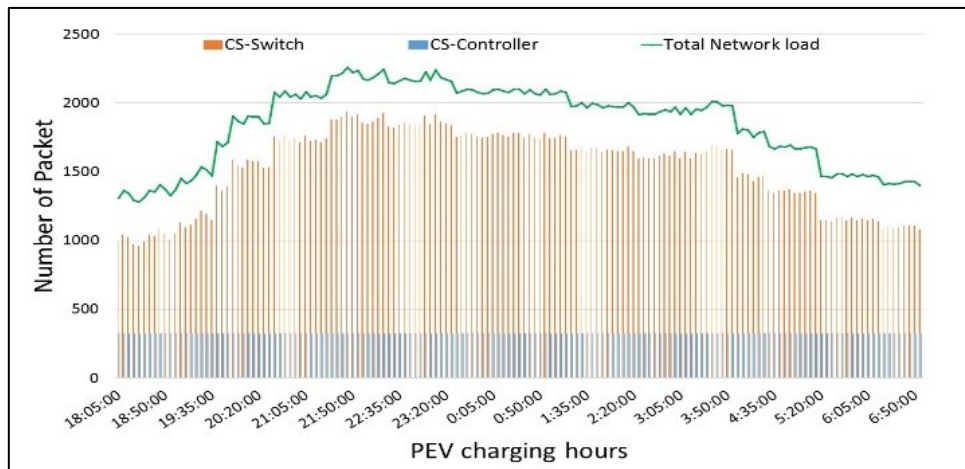


Figure 5.13 Total communication network load

Figure 5.12 shows the consumed power in the individual NANs over the charging period. By careful observation, we notice that there is a sudden drop at the end of the charging hour. This is due to the vehicles that are still in the queue waiting to finish charging. However, these vehicles are expected to have enough charge for the day ahead and trying to reach 100% SoC level.

Figure 5.13 shows the total communication network load of the proposed SDN based G2V system. The communication load between the charging station (CS) and switch varies based on the number of PEVs connected to the network. The CS periodically sends updated information on the connected number of PEVs and their SOC level. The switch to controller communication load is fixed as all of the switches periodically send 12 pph to the controller and receive an acknowledgment for each transmission. Finally, based on the communication parameters summarized in Table 5.1, the total communication load for the charging session is shown in Figure 5.13.

5.5. Summary

In the proposed SDN based NAN communication framework, provided in Chapter 4, a group of IEDs and smart meters form clusters, and a single switch handles each cluster. For large WSNs based NANs, the maximum network throughput and efficiency (e.g. packet success rate) would rely on the optimal number of switches that will be deployed in the distribution grid. Also, robustness of the communication system would depend on intelligent implementation of distributed controllers in the control plane. The mathematical model presented in this chapter determines the optimized number of switches and controllers within the NAN. The minimum number of distributed controllers in a NAN domain is derived and presented graphically. Additionally, this chapter presents a novel SDWSN based G2V load management scheme appropriate traffic models to support the SG during the off-peak hour through efficient Valley filling technique. It's evident through simulation based analysis that the proposed SDN based G2V communication model can successfully support the load management application. Furthermore, a range of simulation models are presented to here to demonstrate the feasibility of the proposed SDN based NAN communication framework for AMI applications. The simulation study considered optimized number of distributed controllers derived from the proposed mathematical model. Simulation results on the AMI traffic in SDN based NAN shows the average delay and success rates of a predefined number of smart meter operation in the NAN domain.

CHAPTER 6. Conclusion and Future Work

The fundamental building block of future smart power systems is a robust communication network with a high degree of flexibility to control the network devices. In the SG literature, there is a focus on proposing solutions to the diverse challenges associated with M2M communications. A wide range of issues needs to be addressed to satisfy the selective requirements of various SG applications. On top of these prerequisites, a smart network and data acquisition approach is mandatory to achieve the high levels of efficiency, accuracy, and performance needed for modern power grid operations. As a mean to develop solutions, wireless technologies offer great potentials where different domains of the power system can stay connected to support various SG applications. In this context, wireless technologies used for SG M2M communications should be enhanced to overcome the challenges, such as integration of vast numbers of devices, excellent network performance and scalability of the network components and applications. Thus, implementing a robust communication system with a well-planned end-to-end network architecture, with the capability to manage the network configuration, is a vital step for SGs to become the norm.

The research questions and the challenges identified were considered sequentially. The key research questions were identified and addressed successfully. In particular, the research carried out revealed that accommodating and configuring a large number of network devices and applications in real-time would be the main bottleneck for SG communication networks. In this thesis, a range of new and innovative solutions have been proposed using various wireless technologies such as Zigbee, WLAN, and WiMAX. The proposed solutions include a novel end-to-end network architecture, traffic models and smart algorithms to satisfy SG application requirements. Furthermore, the proposed solutions exploit the SDN networking paradigm as it offers potential benefits in terms of managing, configuring and controlling the network. The key aspect of SDN, separation of the control plane and data plane, enhances programmability and real-time changes to the SG providing a flexible and efficiency model for SG applications.

This chapter summarizes the key contributions and research outcomes and sheds light on prospective future research directions.

6.1. Contribution Summary

An extensive literature survey on SG applications, traffic characteristic, end-to-end delay requirements and standardization effort was carried out and published. The review classifies the different power grid domains and develops an understanding of the communication network architecture requirements for SGs. Further, the review focused on the key challenges associated with application traffic characterization. It also included SG standardization initiatives from different parts of the world. The study on SG standardization provides a platform to map between power system standards and communication standards contributing to the efficiency of global SG application development. It is evident from this discussion that the future SG communication systems should be robust and support numerous SG applications at any point in the grid, supporting network device configuration and operation while maintaining strict traffic requirements and applying international standards. Therefore, the key challenges identified are to allocate radio resources among various traffic types, prioritizing applications, run-time network management and maintaining QoS.

Based on the literature survey a number of SG applications are proposed in Chapter 3. The simulation models, analysis, and results are provided in Chapter 3 for the particular SG applications. The first application relating to the ZigBee based Pilot protection scheme proposed a new DBPQ technique using the IEEE802.15.4 standard. The simulations were carried out utilizing Castalia, and test bed experiments were conducted using a network of CC2530 chips (ZigBee protocol stack). The results demonstrate that the proposed communication model can operate within the guaranteed delay bounds for the pilot signals. The second application proposed an analytical model for V2G power allocation in an SG scenario. A modified LP algorithm is utilized at the CC to estimate the peak hours, and a WiMAX-WLAN communication network provides robust and reliable transmission between the CC, V2G AP, and vehicles at the parking locations. The results clearly demonstrate that the proposed

energy scheduling scheme increases system reliability and capacity via smart energy allocation and works efficiently to meet variable demand loads. It is anticipated that there will be multiple SG applications running over the network at the same time. The third contribution presented is the enhancement of the WiMAX ranging scheme to accommodate a large number of M2M devices.

The proposed ranging scheme enables a contention free network access to the periodic M2M SG applications. At first, analysis on the existing standalone WiMAX ranging channel is presented in terms of access delay, success rate and access throughput. The OPNET based simulation outcome indicate that at high random-access loads, the access success rate drops sharply and the mean access delay increases exponentially. Then an SG event was generated in the simulation model where the underlying WiMAX network faces a heavy random-access load and the results show that the proposed scheme is able to provide an improved performance in comparison to that of the conventional ranging scheme.

The data generated by SG end users is an increasingly valuable source of information and is used to guide the development and operation of SG applications. Decentralized and distributed deployment of NAN devices makes it challenging to manage SG efficiently. Hence, the overall NAN communication network architecture presented in Chapter 4 is a major contribution. The main objective of this proposed framework is to aggregate and disseminate information among the different SG domains. In this chapter, a complete NAN communication framework based on WSN was developed using the SDN paradigm. The data plane devices such as smart meters, IEDs, sensors and switches are controlled and managed via an optimized number of SDN controllers. A Castalia based simulation model was developed to analyze the network performance. The results obtained demonstrate the reliable traffic dissemination from the different SG applications. Two major flow types were defined, proactive and reactive, to handle the packets generated by either delay tolerant or delay sensitive applications.

Chapter 5 presents an analytical model to determine the optimized number of required switches and

controllers within a NAN to cover a region. The chapter also included a G2V load management scheme based on the SDN networking paradigm. A smart load allocation algorithm is used for off peak valley filling. Simulation results demonstrate successful load balancing during the off-peak hours and reliable network performance. Chapter 5 included an extended simulation scenario to analyze the performance of SDN based delay sensitive AMI applications like outage management. Results obtained from this simulation show the success rate of ‘Last Gasp’ traffic by varying the number of smart meters in the NAN domain.

6.2. Future research direction

Although this research presents the details on M2M communication systems using standalone and heterogeneous wireless networks, a number of prospective future research directions exist. Also, the proposed model of an SDN based SG communication system can be regarded as a starting point for future work in this field as there remain questions about a range of SG implementation scenarios and applications.

The proposed Pilot protection scheme did not include an investigation into multi-terminal protected lines based on multicast communications, which is left as future work. Also, integration of different protection schemes such as POTT and DCB could be future work. To make the proposed Zigbee based Pilot protection scheme more robust, a retransmission scheme could be incorporated while maintaining the tight delay budget.

The PEV load management scheme described in Chapter 3 needs further development. Smart optimization and efficient energy scheduling techniques can be integrated to enhance the performance of the proposed scheme. The proposed scheme approach can be used in other SG applications including micro grids, smart storage systems, DERs and HVAC etc. for optimized energy scheduling and network performance.

The proposed WiMAX ranging provides an improved average delay for the regular periodic

applications. The continuation of this research can include development of packet scheduling and admission control algorithms to support the proposed ranging scheme under SG scenarios. An experimental examination of the performance of the proposed scheme requires future investigation.

The proposed heterogeneous networks could evolve as SDN matures. Limited work has been observed on SDN controller to controller communication in a multi-domain scenario, and future SGs would require multi-domain communication to integrate the end-to-end power grid communication network. An SDN based heterogeneous communication network architecture for distributed SGs would rely upon successful incorporation of multi-domain SDN controller to controller communication.

The proposed SDN based WSN communication system for the SG NAN domain requires further enhancement in terms of a more sophisticated scheme to reduce communication overhead and possible system over design. The proposed optimization scheme for the number of distributed controllers needs further investigation to improve network performance and reduce end-to-end delay. One possible aspect can be the placement of the distributed controllers in the NAN domain. It would also be interesting to exploit the concept of the proposed communication framework to model heterogeneous SDN based SG network architectures.

References

- [1] "The SG: An Introduction," U.S. Department Of Energy (DOE), *Technical Report 2010*. [Online] Available:http://energy.gov/sites/prod/files/oeprprod/DocumentsandMedia/DOE_SG_Book_Single_Pages%281%29.pdf.
- [2] A. Aggarwal, S. Kunta, and P. K. Verma, "A proposed communications infrastructure for the SG," *Innovative SG Technologies (ISGT)*, pp. 1-5, 2010.
- [3] R. Hledik, "How Green Is the SG?," *The Electricity Journal*, vol. 22, pp. 29-41, 2009.
- [4] "Australia's Abatement Task And 2013 Emissions Projections," A. G. Dept. Of Environment, Ed., ed, 2013.
- [5] "Business Go Solar to Save Millions," ed: *Clean Energy Council*, Australia, 2014.
- [6] "Energy Market Arrangements For Electric And Natural Gas Vehicles," *Technical Report*, January 2012.
- [7] L. Fangxing, Q. Wei, S. Hongbin, W. Hui, W. Jianhui, X. Yan, et al., "Smart Transmission Grid: Vision and Framework," *IEEE Transactions on SG*, vol. 1, pp. 168-177, 2010.
- [8] V. C. Gungor, D. Sahin, T. Kocak, S. Ergut, C. Buccella, C. Cecati, et al., "A Survey on SG Potential Applications and Communication Requirements," *IEEE Transactions on Industrial Informatics*, vol. 9, pp. 28-42, 2013.
- [9] Towards Australia's Energy Future: The Enabling Role of SGs. (2012) [Online] Available: http://smartgridaustralia.com.au/SGA/Documents/Publication_120914.pdf
- [10] B. Hamilton and M. Summy, "Benefits of the SG [In My View]," *IEEE Power and Energy Magazine*, vol. 9, pp. 104-102, 2011.
- [11] "Understanding The Benefits Of The SG," *National Energy Technology Laboratory*, 18 June 2010.
- [12] P. Mallet, P. O. Granstrom, P. Hallberg, G. Lorenz, and P. Mandatova, "Power to the People!: European Perspectives on the Future of Electric Distribution," *IEEE Power and Energy Magazine*, vol. 12, pp. 51-64, 2014.
- [13] C. Kwang-Cheng, Y. Ping-Cheng, H. Hung-Yun, and S. C. Chang, "Communication infrastructure of SG," 4th International Symposium on Communications, *Control and Signal Processing (ISCCSP)*, pp. 1-5, 2010
- [14] M. Erol-Kantarci and H. T. Mouftah, "Energy-Efficient Information and Communication Infrastructures in the SG: A Survey on Interactions and Open Issues," *IEEE Communications Surveys & Tutorials*, vol. 17, pp. 179-197, 2015.
- [15] C. Kalalas, L. Thrybom, and J. Alonso-Zarate, "Cellular Communications for SG Neighborhood Area Networks: A Survey," *IEEE Access*, vol. 4, pp. 1469-1493, 2016.
- [16] Y. Ye, Q. Yi, H. Sharif, and D. Tipper, "A Survey on SG Communication Infrastructures: Motivations, Requirements and Challenges," *IEEE Communications Surveys & Tutorials*, vol. 15, pp. 5-20, 2013.
- [17] Q. Yan, F. R. Yu, Q. Gong and J. Li, "Software-Defined Networking (SDN) and Distributed Denial of Service (DDoS) Attacks in Cloud Computing Environments: A Survey, Some Research Issues, and Challenges," *IEEE Transactions on Industrial Electronics*, vol. 57, no. 10, pp. 3557-3564, Oct. 2010. doi: 10.1109/TIE.2009.2039455
- [18] V. C. Gungor, B. Lu and G. P. Hancke, "Opportunities and Challenges of Wireless Sensor Networks in SG," *IEEE Transactions on Industrial Electronics*, vol. 57, no. 10, pp. 3557-3564, Oct. 2010. doi: 10.1109/TIE.2009.2039455
- [19] R. Chaparadza et al., "SDN enablers in the ETSI AFI GANA Reference Model for Autonomic Management & Control (emerging standard), and Virtualization impact," *IEEE Globecom Workshops (GC Wkshps)*, Atlanta, GA, 2013, pp. 818-823. doi: 10.1109/GLOCOMW.2013.6825090
- [20] Open Networking Foundation (2013). Openflow Switch Specification, version 1.3.0 (Wire Protocol 0x05), Retrieved from <https://www.opennetworking.org/images/stories/downloads/sdn-resources/onf-specifications/openflow/openflow-spec-v1.4.0.pdf>.
- [21] Reduan H. Khan, Jamil Y. Khan, "A comprehensive review of the application characteristics and traffic requirements of a SG communications network," *Computer Networks*, Volume 57, Issue 3, 26 February 2013, Pages 825-845, ISSN 1389-1286]
- [22] A. Molderink, V. Bakker, M. G. C. Bosman, J. L. Hurink, and G. J. M. Smit, "Management and control of domestic SG technology," *IEEE Transaction on SG*, 1(2):109-119, 2010.
- [23] B. Kroposki, R. Margolis, G. Kuswa, J. Torres, W. Bower, T. Key, and D. Ton., "Renewable systems interconnection: Executive summary," *Technical Report NREL/TP-581-42292*, U.S. Department of Energy, 2008.
- [24] F. Benzi, N. Anglani, E. Bassi, and L. Frosini, "Electricity smart meters interfacing the households," *IEEE Transaction On Industrial Electronics*, vol. 58, no. 10, pp. 4487-4494, Oct. 2011
- [25] Ruilong Deng; Zaiyue Yang; Mo-Yuen Chow; Jiming Chen, "A Survey on DR in SGs: Mathematical Models and Approaches," *IEEE Transactions on Industrial Informatics*, vol.11, no.3, pp.570-582, June 2015. doi: 10.1109/TII.2015.2414719
- [26] Andren, F.; Brundlinger, R.; Strasser, T., "IEC 61850/61499 Control of DERs: Concept, Guidelines, and Implementation," *IEEE Transactions on Energy Conversion*, vol.29, no.4, pp.1008-1017, Dec. 2014. doi: 10.1109/TEC.2014.2352338

- [27] Igualada, L.; Corchero, C.; Cruz-Zambrano, M.; Heredia, F.-J., "Optimal Energy Management for a Residential Microgrid Including a Vehicle-to-Grid System," *IEEE Transactions on SG*, vol.5, no.4, pp.2163-2172, July 2014doi: 10.1109/TSG.2014.2318836
- [28] Dorsch, N.; Kurtz, F.; Georg, H.; Hagerling, C.; Wietfeld, C., "Software-defined networking for SG communications: Applications, challenges and advantages," *International Conference on SG Communications (SmartGridComm)*, vol., no., pp.422-427, 3-6 Nov. 2014
- [29] Cahn, A.; Hoyos, J.; Hulse, M.; Keller, E., "Software-defined energy communication networks: From substation automation to future SGs," *IEEE International Conference on SG Communications (SmartGridComm)*, vol., no., pp.558-563, 21-24 Oct. 2013 doi: 10.1109/SmartGridComm.2013.6688017
- [30] S. Mohagheghi, J. Stoupi, Z Wang, "Communication protocols and networks for power systems-current status and future trends," *Power Systems Conference and Exposition*, March 2009
- [31] N. Himayat, S. Talwar, K. Johnsson, X. Wang, "Functional Requirements for Network Entry and Random Access by Large Number of Devices," *IEEE 802.16p Task Group*, September, 2010.
- [32] "West Virginia SG Implementation Plan (WV SGIP) Project: APERC Report on Assessment of As-Is Grid by Non-Utility Stakeholders," December 2009.
- [33] "NIST Framework And Roadmap For SG Interoperability Standards," *ed: NIST*, 2010.
- [34] "IEEE Guide for SG Interoperability of Energy Technology and Information Technology Operation with the Electric Power System (EPS), End-Use Applications, and Loads," *IEEE Std 2030*, pp. 1-126, 2011.
- [35] X. Fang, S. Misra, G. Xue, and D. Yang, "SG - The New and Improved Power Grid: A Survey," *IEEE Communications Surveys & Tutorials*, vol. 14, pp. 944-980, 2012.
- [36] N. S. Nafi, K. Ahmed, M. Datta, and M. A. Gregory, "A novel Zigbee based pilot protection scheme for smart distribution grid," *Australasian Telecommunication Networks and Applications Conference (ATNAC)*, pp. 146-151, 2014.
- [37] H. Gharavi and H. Bin, "Multigate Communication Network for SG," *Proceedings of the IEEE*, vol. 99, pp. 1028-1045, 2011.
- [38] "IEEE Draft Standard for Information Technology - Telecommunications and Information Exchange Between Systems - Local and Metropolitan Area Networks - Specific Requirements - Part 15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low Rate Wireless Personal Area Networks (WPANs) Amendment: Alternative Physical Layer Extension to support Medical Body Area Network (MBAN) services operating in the 2360-2400 MHz band," *IEEE P802.15.4j/D4.0*, September 2012 (Amendment of IEEE Std. 802.15.4-2011), pp. 1-19, 2012.
- [39] A. S. Cacciapuoti, M. Caleffi, F. Marino, and L. Paura, "Enabling SG via TV White Space Cognitive Radio," *IEEE International Conference on Communication Workshop (ICCW)*, pp. 568-572, 2015.
- [40] M. No-Gil, K. Younhyun, and L. Sangyeom, "The design of communication infrastructures for smart DAS and AMI," *International Conference on Information and Communication Technology Convergence (ICTC)*, pp. 461-462, 2010
- [41] "Wimax Applications For Utilities," *Wimax Forum*, 2008.
- [42] J. Ji-Sun, L. Keun-Woo, K. Jae-Beom, K. Young-Bae, K. Younhyun, and L. Sang-Yeom, "Improving IEEE 802.11s Wireless Mesh Networks for Reliable Routing in the SG Infrastructure," *IEEE International Conference on Communications Workshops (ICC)*, pp. 1-5, 2011
- [43] T. Basso, J. Hambrick, and D. DeBlasio, "Update and review of IEEE P2030 SG Interoperability and IEEE 1547 interconnection standards," *Innovative SG Technologies (ISGT)*, IEEE PES, 2012, pp. 1-7, 2012
- [44] "IEEE Draft Guide for the Interoperability of Energy Storage Systems Integrated with the Electric Power Infrastructure," *IEEE P2030.2/D8.0*, October 2014, pp. 1-134, 2014.
- [45] M. Ruta, F. Scioscia, E. Di Sciascio, and G. Loieto, "Semantic-Based Enhancement of ISO/IEC 14543-3 EIB/KNX Standard for Building Automation," *IEEE Transactions on Industrial Informatics*, vol. 7, pp. 731-739, 2011.
- [46] I. S. O. (ISO), "ISO 16484-5, Building automation and control systems —Part 5: Data communication protocol," 2007.
- [47] "Australian Standards For SGs- Standards Roadmap, Standards Australia (SA)," June 2012.
- [48] N. E. M. Association, "American National Standard for Protocol Specification for ANSI Type 2 Optical Port, ANSI C12.18," *NEMA*, 2006.
- [49] "Final Report Of The CEN/CENELEC/ETSI Joint Working Group On Standards For SGs," 2011.
- [50] "Standardization Mandate to European Standardisation Organisations (ESOs) to Support European SG Deployments," March 2011.
- [51] M. Uslar, S. Rohjans, R. Bleiker, J. Gonzalez, M. Specht, T. Suding, et al., "Survey of SG standardization studies and recommendations-Part 2," *Innovative SG Technologies Conference Europe (ISGT Europe)*, IEEE PES, 2010, pp. 1-6, 2010.
- [52] "IEEE Standard for Utility Industry Metering Communication Protocol Application Layer (End Device Data Tables)," *IEEE Std 1377-2012 (Revision of IEEE Std 1377-1997)*, pp. 1-576, 2012.

- [53] "IEEE Standard for Optical Port Communication Protocol to Complement the Utility Industry End Device Data Tables," *IEEE Std 1701-2011*, pp. 1-50, 2011.
- [54] "IEEE Standard for Telephone Modem Communication Protocol to Complement the Utility Industry End Device Data Tables," *IEEE Std 1702-2011*, pp. 1-73, 2011.
- [55] "IEEE Standard for Local Area Network/Wide Area Network (LAN/WAN) Node Communication Protocol to Complement the Utility Industry End Device Data Tables," in *IEEE Std 1703-2012*, vol., no., pp.1-239, June 29 2012. doi: 10.1109/IEEESTD.2012.6226334
- [56] "IEEE Standard for Ethernet - Section 2," *IEEE Std 802.3-2012 (Revision to IEEE Std 802.3-2008)*, pp. 1-0, 2012.
- [57] "IEEE Standard for Local and Metropolitan Area Networks-- Station and Media Access Control Connectivity Discovery," *IEEE Std 802.1AB-2009 (Revision of IEEE Std 802.1AB-2005)*, pp. 1-204, 2009.
- [58] "IEEE Standard for Local and metropolitan area networksMedia Access Control (MAC) Security Amendment 2: Extended Packet Numbering," *IEEE Std 802.1AEbw-2013 (Amendment to IEEE Std 802.1AE-2006)*, pp. 1-67, 2013.
- [59] "IEEE Standard for Local and metropolitan area networks - Secure Device Identity," *IEEE Std 802.1AR-2009*, pp. 1-77, 2009.
- [60] "IEEE Standard for Local and metropolitan area networks--Link Aggregation Amendment 1: Protocol Addressing," *IEEE Std 802.1AXbk-2012 (Amendment to IEEE Std 802.1AX-2008)*, pp. 1-60, 2012.
- [61] "IEEE Standard for Local and metropolitan area networks -- Port-Based Network Access Control Amendment 1: MAC Security Key Agreement Protocol (MKA) Extensions," *IEEE Std 802.1Xbx-2014 (Amendment to IEEE Std 802.1X-2010)*, pp. 1-107, 2014.
- [62] "IEEE Standard for Information Technology - Telecommunications and Information Exchange Between Systems - Local and Metropolitan Area Networks - Specific Requirements - Part 2: Logical Link Control," *ISO 8802-2 IEEE 802.2, First Edition 1989-12-31 (Revision of IEEE Std 802.2-1985)*, pp. 1-114, 2013.
- [63] "IEEE Standard for Ethernet Amendment 2: Physical Layer Specifications and Management Parameters for 100 Gb/s Operation Over Backplanes and Copper Cables," *IEEE Std 802.3bj-2014 (Amendment to IEEE Std 802.3-2012 as amended by IEEE Std 802.3bk-2013)*, pp. 1-368, 2014.
- [64] "IEEE Standard for Information technology--Telecommunications and information exchange between systems Local and metropolitan area networks--Specific requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications," *IEEE P802.11-REVmb/D12, November 2011 (Revision of IEEE Std 802.11-2007, as amended by IEEE Std 802.11k-2008, 802.11r-2008, 802.11y-2008, 802.11w-2009, 802.11n-2009, 802.11p-2010, 802.11z-2010, 802.11v-2011, 802.11u-2011, and 802.11s-2011)*, pp. 1-2910, 2012.
- [65] "IEEE Standard for Information Technology - Telecommunications and Information Exchange Between Systems - Local and Metropolitan Area Networks - Specific Requirements. - Part 15.1: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Wireless Personal Area Networks (WPANs)," *IEEE Std 802.15.1-2005 (Revision of IEEE Std 802.15.1-2002)*, pp. 0_1-580, 2005.
- [66] "IEEE Standard for Local and metropolitan area networks - Part 15.4: Low-Rate Wireless Personal Area Networks (LR-WPANs) - Amendment 6: TV White Space Between 54 MHz and 862 MHz Physical Layer," *IEEE Std 802.15.4m-2014 (Amendment to IEEE Std 802.15.4-2011 as amended by IEEE Std 802.15.4e-2012, IEEE Std 802.15.4f-2012, IEEE Std 802.15.4g-2012, IEEE Std 802.15.4j-2013, and IEEE Std 802.15.4k-2013)*, pp. 1-118, 2014.
- [67] "IEEE Standard for Local and metropolitan area networks--Part 15.4: Low-Rate Wireless Personal Area Networks (LR-WPANs) Amendment 1: MAC sublayer," *IEEE Std 802.15.4e-2012 (Amendment to IEEE Std 802.15.4-2011)*, pp. 1-225, 2012.
- [68] "IEEE Standard for Local and metropolitan area networks--Part 15.4: Low-Rate Wireless Personal Area Networks (LR-WPANs) Amendment 3: Physical Layer (PHY) Specifications for Low-Data-Rate, Wireless, Smart Metering Utility Networks," *IEEE Std 802.15.4g-2012 (Amendment to IEEE Std 802.15.4-2011)*, pp. 1-252, 2012.
- [69] "IEEE Standard for Air Interface for Broadband Wireless Access Systems," *IEEE Std 802.16-2012 (Revision of IEEE Std 802.16-2009)*, pp. 1-2542, 2012.
- [70] "IEEE Standard for Air Interface for Broadband Wireless Access Systems--Amendment 2: Higher Reliability Networks," *IEEE Std 802.16n-2013 (Amendment to IEEE Std 802.16-2012)*, pp. 1-168, 2013.
- [71] "IEEE Standard for Air Interface for Broadband Wireless Access Systems--Amendment 1: Enhancements to Support Machine-to-Machine Applications," *IEEE Std 802.16p-2012 (Amendment to IEEE Std 802.16-2012)*, pp. 1-82, 2012.
- [72] "IEEE Standard for WirelessMAN-Advanced Air Interface for Broadband Wireless Access Systems," *IEEE Std 802.16.1-2012*, pp. 1-1090, 2012.
- [73] "IEEE Standard for WirelessMAN-Advanced Air Interface for Broadband Wireless Access Systems -- Amendment 2: Higher Reliability Networks," *IEEE Std 802.16.1a-2013 (Amendment to IEEE Std 802.16.1-2012)*, pp. 1-319, 2013.

- [74] "IEEE Standard for WirelessMAN-Advanced Air Interface for Broadband Wireless Access Systems Amendment 1: Enhancements to Support Machine-to-Machine Applications," *IEEE Std 802.16.1b-2012 (Amendment to IEEE Std 802.16.1-2012)*, pp. 1-126, 2012.
- [75] "IEEE Standard for Local and Metropolitan Area Networks Part 20: Air Interface for Mobile Broadband Wireless Access Systems Supporting Vehicular Mobilityphysical and Media Access Control Layer Specification," *IEEE Std 802.20-2008*, pp. 1-1039, 2008.
- [76] "IEEE Standard for Broadband over Power Line Networks: Medium Access Control and Physical Layer Specifications," *IEEE Std 1901-2010*, pp. 1-1586, 2010.
- [77] "IEEE Guide for Electric Power Substation Physical and Electronic Security," IEEE Std 1402-2000, p. i, 2000.
- [78] "IEEE Standard for Intelligent Electronic Devices Cyber Security Capabilities," IEEE Std 1686-2013 (Revision of IEEE Std 1686-2007), pp. 1-29, 2014.
- [79] "IEEE Trial-Use Standard for a Cryptographic Protocol for Cyber Security of Substation Serial Links," IEEE Std 1711-2010, pp. 1-49, 2011
- [80] "IEEE Recommended Practice for Data Communications Between Remote Terminal Units and Intelligent Electronic Devices in a Substation," IEEE Std 1379-2000, pp. 1-72, 2001.
- [81] "IEEE Recommended Practice for Network Communication in Electric Power Substations," IEEE Std 1615-2007, pp. 1-89, 2007.
- [82] "IEEE Standard Communication Delivery Time Performance Requirements for Electric Power Substation Automation," IEEE Std 1646-2004, pp. 0_1-24, 2005.
- [83] "IEEE Standard for Electric Power Systems Communications-Distributed Network Protocol (DNP3)," IEEE Std 1815-2012 (Revision of IEEE Std 1815-2010), pp. 1-821, 2012.
- [84] "IEEE Standard for N Times 64 Kilobit Per Second Optical Fiber Interfaces Between Teleprotection and Multiplexer Equipment," IEEE Std C37.94-2002, p. 0_1, 2003.
- [85] "IEEE/IEC Measuring relays and protection equipment Part 24: Common format for transient data exchange (COMTRADE) for power systems," IEEE Std C37.111-2013 (IEC 60255-24 Edition 2.0 2013-04), pp. 1-73, 2013.
- [86] "IEEE Standard for Synchrophasor Data Transfer for Power Systems," IEEE Std C37.118.2-2011 (Revision of IEEE Std C37.118-2005), pp. 1-53, 2011.
- [87] "IEEE Standard for SCADA and Automation Systems," IEEE Std C37.1-2007 (Revision of IEEE Std C37.1-1994), pp. 1-143, 2008.
- [88] "IEEE Recommended Practice for Microprocessor-Based Protection Equipment Firmware Control," IEEE Std C37.231-2006, pp. 1-25, 2007.
- [89] "IEEE Recommended Practice for Naming Time Sequence Data Files," IEEE Std C37.232-2007, pp. C1-15, 2007.
- [90] "IEEE Standard for Common Format for Naming Time Sequence Data Files (COMNAME)," IEEE Std C37.232-2011 (Revision of IEEE Std C37.232-2007), pp. 1-25, 2011.
- [91] "IEEE Guide for Power System Protective Relay Applications Over Digital Communication Channels," IEEE Std C37.236-2013, pp. 1-84, 2013.
- [92] "IEEE Standard Profile for Use of IEEE 1588 Precision Time Protocol in Power System Applications," IEEE Std C37.238-2011, pp. 1-66, 2011.
- [93] "IEEE Standard for Common Format for Event Data Exchange (COMFEDE) for Power Systems," IEEE Std C37.239-2010, pp. 1-72, 2010
- [94] "IEEE Draft Guide for the Interoperability of Energy Storage Systems Integrated with the Electric Power Infrastructure," *IEEE P2030.2/D8.0, October 2014*, pp. 1-134, 2015.
- [95] "IEEE Guide for Monitoring, Information Exchange, and Control of Distributed Resources Interconnected with Electric Power Systems," IEEE Std 1547.3-2007, pp. 1-160, 2007.
- [96] "IEEE Draft Standard for Local Area Network/Wide Area Network (LAN/WAN) Node Communication Protocol to complement the Utility Industry End Device Data Tables," IEEE P1703/D9, February 2012, pp. 1-253, 2012.
- [97] "IEEE Recommended Practice for the Transfer of Power Quality Data," *IEEE Std 1159.3-2003*, pp. 0_1-119, 2004.
- [98] "IEEE Standard for Low-Frequency (less than 500 kHz) Narrowband Power Line Communications for Smart Grid Applications," *IEEE Std 1901.2-2013*, pp. 1-269, 2013.
- [99] W. Yong, R. Da, G. Dawu, J. Gao, L. Daming, X. Jianping, *et al.*, "Analysis of Smart Grid security standards," in *Computer Science and Automation Engineering (CSAE), 2011 IEEE International Conference on*, 2011, pp. 697-701
- [100] S. Rohjans, M. Uslar, R. Bleiker, Gonza, x, J. Iez, *et al.*, "Survey of Smart Grid Standardization Studies and Recommendations," *First IEEE International Conference on Smart Grid Communications (SmartGridComm)*, pp. 583-588, 2010.
- [101] I. E. C. (IEC), "61970-301 Ed. 1: Energy management system application program interface (EMS-API) - Part 301: Common information model (CIM) base," ed: IEC STD, 2007.
- [102] I. E. C. (IEC), "61968-11 Ed. 1: System Interfaces for Distribution Management – Part 11: Distribution Information Exchange Model," ed: IEC STD, 2008.

- [103] IEC, "61850-1 Communication networks and systems in substations - Part 1: Introduction and overview," ed: International Electrotechnical Commission 2003
- [104] I. Std., "62351-1 TS Ed.1: Data and communication security - Part 1: Introduction and overview," ed: International Electrotechnical Commission, 2006.
- [105] I. Std., "62357 Second Edition: TC 57 Architecture - Part 1: Reference Architecture for TC 57 - Draft," ed: International Electrotechnical Commission, 2009.
- [106] I. Std., "60870 Ed.2: Telecontrol equipment and systems - Part 5-101: Transmission protocols-Companion standard for basic telecontrol tasks," ed: International Electrotechnical Commission, 2003.
- [107] I. Std., "60870 Ed.2: Telecontrol equipment and systems - Part 5-104: Transmission protocols-Network access for IEC 60870-5-101 using standard transport profiles," ed: International Electrotechnical Commission, 2006.
- [108] I. Std., "60870 Telecontrol equipment and systems - Part 6-503: Telecontrol protocols compatible with ISO standards and ITU-T recommendations TASE.2 Services and protocol," ed: International Electrotechnical Commission 2003.
- [109] I. Std., "61400 WIND TURBINES Part 25-1: Communications for monitoring and control of wind power plants - Overall description of principles and models, IEC Std," ed: International Electrotechnical Commission, 2006.
- [110] I. Std., "61334 Distributed Automation Using Distribution Line Carrier Systems Part 4: Data Communication Protocols; Section 4: Application Protocol; Clause 1: Distribution Line Message Specification (DLMS)," ed: International Electrotechnical Commission, 1996.
- [111] I. Std., "62056 Electricity metering - Data exchange for meter reading, tariff and load control- Part 47: COSEM transport layers for IPv4 networks," ed: International Electrotechnical Commission 2006.
- [112] I. Std., "62325-101 DTR Ed.1: Framework for energy market communications -Part 101: General guidelines and requirements," ed: International Electrotechnical Commission, 2004.
- [113] M. Salehie, L. Pasquale, I. Omoronyia, and B. Nuseibeh, "Adaptive security and privacy in smart grids: A software engineering vision," International Workshop on, Software Engineering for the Smart Grid (SE4SG), pp. 46-49, 2012.
- [114] K. J. Ross, K. M. Hopkinson, and M. Pachter, "Using a Distributed Agent-Based Communication Enabled Special Protection System to Enhance Smart Grid Security," IEEE Transactions on Smart Grid, vol. 4, pp. 1216-1224, 2013.
- [115] F. Benzi, N. Anglani, E. Bassi, and L. Frosini, "Electricity Smart Meters Interfacing the Households," Industrial Electronics, IEEE Transactions on, vol. 58, pp. 4487-4494, 2011.
- [116] V. C. Gungor, D. Sahin, T. Kocak, S. Ergut, C. Buccella, C. Cecati, et al., "Smart Grid and Smart Homes: Key Players and Pilot Projects," Industrial Electronics Magazine, IEEE, vol. 6, pp. 18-34, 2012.
- [117] S. Paudyal, C. A. Canizares, and K. Bhattacharya, "Optimal Operation of Distribution Feeders in Smart Grids," Industrial Electronics, IEEE Transactions on, vol. 58, pp. 4495-4503, 2011.
- [118] T. Sauter and M. Lobashov, "End-to-End Communication Architecture for Smart Grids," IEEE Transactions on Industrial Electronics, , vol. 58, pp. 1218-1228, 2011.
- [119] A. Zaballos, A. Vallejo, and J. M. Selga, "Heterogeneous communication architecture for the smart grid," Network, IEEE, vol. 25, pp. 30-37, 2011.
- [120] "American national standard for utility industry end device data tables," ed: ANSI C12.19, 2009.
- [121] L. Guangxian and L. Haitao, "Study on IEC 61970/61968 based information integration for smart distribution grid," IEEE Transactions on Electrical and Control Engineering (ICECE), pp. 5019-5022, 2011.
- [122] "NIST Priority Action Plan 2 Guidelines for Assessing Wireless Standards for Smart Grid Applications," U.S. Department of Commerce, February 2011.
- [123] Nazmus S. Nafi, Khandakar Ahmed, Mark A. Gregory, Manoj Datta, "A survey of smart grid architectures, applications, benefits and standardization," *Journal of Network and Computer Applications*, vol 76, pp 23-36, ISSN 1084-8045, 2016.
- [124] C. Cecati, C. Citro, and P. Siano, "Combined Operations of Renewable Energy Systems and Responsive Demand in a Smart Grid," IEEE Transactions on Sustainable Energy, vol. 2, pp. 468-476, 2011.
- [125] C. Cecati, C. Citro, A. Piccolo, and P. Siano, "Smart Operation of Wind Turbines and Diesel Generators According to Economic Criteria," IEEE Transactions on Industrial Electronics, vol. 58, pp. 4514-4525, 2011.
- [126] "Communications Requirements of Smart Grid Technologies," October 2010.
- [127] V. Terzija, G. Valverde, C. Deyu, P. Regulski, V. Madani, J. Fitch, et al., "Wide-Area Monitoring, Protection, and Control of Future Electric Power Networks," Proceedings of the IEEE, vol. 99, pp. 80-93, 2011.
- [128] "Application of Peer-to-Peer Communication for Protective Relaying," *Power Engineering Review, IEEE*, vol. 22, pp. 61-61, 2002.
- [129] E. O. Schweitzer, III, K. Behrendt, T. Lee, and D. A. Tziouvaras, "Digital communications for power system protection: security, availability, and speed," *Seventh International Conference on (IEE) Developments in Power System Protection*, 2001, pp. 94-97, 2001.
- [130] R. Hunt, M. Adamiak, A. King, and S. McCreery, "Application of digital radio for distribution pilot protection," in Rural Electric Power Conference, 2008 IEEE, pp. A3-A3-8. 2008.

- [131] A. P. Apostolov, "IEC 61850 communications based transmission line protection," in *Developments 11th International Conference on Power Systems Protection, DPSP*, pp. 1-6, 2012.
- [132] M. P. Sanders, "Object modeling for pilot channel equipment in IEC61850 based devices," in 63rd Annual Conference for Protective Relay Engineers, pp. 1-12, 2010.
- [133] R. H. Khan, J. Brown, and J. Y. Khan, "Pilot protection schemes over a multi-service WiMAX network in the smart grid," *IEEE International Conference on in Communications Workshops (ICC)*, pp. 994-999, 2013.
- [134] A. Smit, "Method and system for programming and implementing automated fault isolation and restoration using sequential logic," ed: Google Patents, 2012.
- [135] J. M. Maciejowski, *Predictive Control with Constraint*. Essex, England: Prentice Hall, 2001.
- [136] P. Mirchandani and L. Head, "A real-time traffic signal control system: architecture, algorithms, and analysis," *Transportation Research Part C: Emerging Technologies*, vol. 9, pp. 415-432, 12// 2001.
- [137] J. S. T. A.G. Phadke, "Synchronized Phasor Measurements and Their Applications," ed: Springer US, 2008.
- [138] S. Xuejian, J. Jian, B. Wei, C. Ji, and W. Kangyuan, "Researches on information framework of Smart Distribution Grid," *China International Conference on Electricity Distribution (CICED)*, 2010, pp. 1-6.
- [139] M. Wache and D. C. Murray, "Application of Synchrophasor Measurements for distribution networks," in *Power and Energy Society General Meeting, IEEE*, pp. 1-4, 2011.
- [140] IEC 61850-90-5 Standard, "Communication networks and systems for power utility automation", May 2012.
- [141] I. Petri, Z. Mengsong, A.R. Zamani, J. Diaz-Montes, O. Rana, M. Parashar, "Integrating Software Defined Networks within a Cloud Federation," *15th IEEE/ACM International Symposium on Cluster, Cloud and Grid Computing (CCGrid)*, pp.179-188, doi: 10.1109/CCGrid, May 2015.
- [142] B. Ahlgren, C. Dannewitz, C. Imbrenda, D. Kutscher, B. Ohlman, "A survey of information-centric networking," *IEEE Commun. Mag.*, 50 (7), pp. 26-36, 2012.
- [143] L. E. Li, Z. M. Mao, and J. Rexford, "Toward software-defined cellular networks", *Proc. of European Workshop on Software Defined Networks (EWSN)*, Darmstadt, Germany October 2012.
- [144] L. Veltri et al., "Supporting information-centric functionality in software defined networks", *Proc. IEEE International Conference on Communications (ICC)*, Ottawa, Canada, June 2012.
- [145] S. Lukovic et al., "Virtual power plant as a bridge between DERs and SG", *Proc. of 43rd Hawaii International Conference on System Sciences (HICSS)*, Kauai, HI, USA, January 2010.
- [146] V. C. Gungor, L. Bin, G.P. Hancke, "Opportunities and Challenges of WSNs in SG," *IEEE Transactions on Industrial Electronics*, vol.57, no.10, pp.3557-3564, doi: 10.1109/TIE.2009.2039455, Oct 2010M.
- [147] M. Kuzlu, M. Pipattanasomporn, S. Rahman, "Communication network requirements for major SG applications in HAN, NAN and WAN," *Computer Networks*, Volume 67, Pages 74-88, ISSN 1389-1286, July 2014, [online] <http://dx.doi.org/10.1016/j.comnet.2014.03.029>
- [148] K. H. Chang, B. Mason, "The IEEE 802.15.4g standard for smart metering utility networks," *IEEE Third International Conference on SG Communications (SmartGridComm)*, 5-8 Nov. 2012. doi: 10.1109/SmartGridComm.2012.6486030.
- [149] J. Zhou, R. Qingyang Hu and Y. Qian, "Scalable Distributed Communication Architectures to Support Advanced Metering Infrastructure in SG," *IEEE Transactions on Parallel and Distributed Systems*, vol. 23, no. 9, pp. 1632-1642, Sept. 2012. doi: 10.1109/TPDS.2012.53
- [150] E. Toscano, L. Bello, "Comparative assessments of IEEE 802.15.4/ZigBee and 6LoWPAN for low-power industrial WSNs in realistic scenarios," *Factory Communication Systems (WFCS)*, 2012 9th IEEE International Workshop on, May 2012
- [151] R. Burchfield and S. Venkatesan, D. Weiner, "Maximizing Throughput in ZigBee Wireless Networks through Analysis, Simulations and Implementations," *Wireless Monitoring Solutions*, Signal Technology. A Crane Co.
- [152] K. K. Yap, M. Kobayashi, R. Sherwood, T. Y. Huang, M. Chan, N. Handigol and N. McKeown, "OpenRoads: Empowering 13th Annual IEEE Workshop on Wireless Local Networks 2013 934 research in mobile networks," *ACM SIGCOMM Computer Communication Review*, vol. 40, no. 1, 2010, pp. 125-126
- [153] J. Kim, F. Filali and Y. B. Ko, "A lightweight CoAP-based software defined networking for resource constrained AMI devices," *IEEE International Conference on SG Communications (SmartGridComm)*, Miami, FL, 2015, pp. 719-724. doi: 10.1109/SmartGridComm.2015.7436386
- [154] "IEEE Standard for Local and metropolitan area networks--Part 15.4: Low-Rate Wireless Personal Area Networks (LR-WPANs) Amendment 3: Physical Layer (PHY) Specifications for Low-Data-Rate, Wireless, Smart Metering Utility Networks," *IEEE Std 802.15.4g-2012 (Amendment to IEEE Std 802.15.4-2011)*, vol., no., pp.1-252, April, 2012. doi: 10.1109/IEEESTD.2012.6190698
- [155] R. H. Khan and J. Y. Khan, "A heterogeneous WiMAX-WLAN network for AMI communications in the SG," *IEEE Third International Conference on SG Communications (SmartGridComm)*, Tainan, pp. 710-715, 2012, doi: 10.1109/SmartGridComm.2012.6486070
- [156] L. Liu, Y. Liu, L. Wang, A. Zomaya and S. Hu, "Economical and Balanced Energy Usage in the Smart Home Infrastructure: A Tutorial and New Results," *IEEE Transactions on Emerging Topics in Computing*, vol. 3, no. 4, pp. 556-570, Dec. 2015. doi: 10.1109/TETC.2015.2484839

- [157] R. E. Mackiewicz, "Overview of IEC 61850 and Benefits," *IEEE PES Power Systems Conference and Exposition*, Atlanta, GA, pp. 623-630, 2006, doi: 10.1109/PSCE.2006.296392
- [158] C. Pirak, T. Sangsuwan and S. Buayairaksa, "Recent advances in communication technologies for SG application: A review," *International Electrical Engineering Congress (iEECON)*, Chonburi, pp. 1-4, 2014. doi: 10.1109/iEECON.2014.6925952
- [159] Guobin Xu, P. Moulema and Wei Yu, "Integrating DERs in SG: Modeling and analysis," *IEEE Energytech*, Cleveland, OH, pp. 1-5, 2013. doi: 10.1109/EnergyTech.2013.6645324
- [160] D. Ginting, A. Fahmi and A. Kurniawan, "Performance evaluation of inter-cell interference of LTE-A system using carrier aggregation and CoMP techniques," *9th International Conference on Telecommunication Systems Services and Applications (TSSA)*, Bandung, pp. 1-5, 2015. doi: 10.1109/TSSA.2015.7440427
- [161] S. S. Das, P. Chandhar, S. Mitra and P. Ghosh, "Issues in Femtocell Deployments in Broadband OFDMA Networks: 3GPP-LTE a Case Study," *IEEE Vehicular Technology Conference (VTC Fall)*, San Francisco, CA, 2011, pp. 1-5. doi: 10.1109/VETECF.2011.6093191
- [162] M. Hadley, J. McBride, T. Edgar, L. O'Neil, J. Johnson, "Securing Wide Area Measurement Systems. Pacific Northwest National Laboratory to U.S. Department of Energy (DOE)". Retrieved from http://www.energy.gov/sites/prod/files/oeprod/DocumentsandMedia/8-Securing_WAMS.pdf
- [163] C. Guille, G. Gross, "Design of a Conceptual Framework for the V2G Implementation," *IEEE Energy 2030 Conference*, November, 2008.
- [164] M. Duvall, E. Knipping, "Environmental assessment of plug-in hybrid electric vehicles. Volume 1: Nationwide Greenhouse Gas Emissions," *EPRI/NRDC*, Palo Alto, CA, Final Rep. 1015325, pp. 1-56, 2007.
- [165] M. Yilmaz, P. T. Krein, "Review of the Impact of Vehicle-to-Grid Technologies on Distribution Systems and Utility Interfaces," *IEEE Transactions on Power Electronics*, vol.28, no.12, pp.5673,5689, December 2013.
- [166] W. Kempton, J. Tomic, "Vehicle-to-grid power implementation: From stabilizing the grid to supporting large-scale renewable energy," *Journal of Power Sources*, Volume 144, Issue 1, Pages 280-294, ISSN 0378-7753, June 2005.
- [167] F. Kennel, D. Görges and S. Liu, "Energy Management for SGs With Electric Vehicles Based on Hierarchical MPC," *IEEE Transactions on Industrial Informatics*, vol. 9, no. 3, pp. 1528-1537, Aug. 2013. doi: 10.1109/TII.2012.2228876
- [168] J. AP. Lopes, F.J. Soares, P.M.R. Almeida, "Integration of Electric Vehicles in the Electric Power System," *IEEE Proceedings*, vol.99, no.1, pp.168,183, January 2011.
- [169] N. S. Nafi, K. Ahmed and M. A. Gregory, "A novel vehicle to grid load management scheme based on WiMAX-WLAN in SGs," *2015 IEEE Wireless Communications and Networking Conference (WCNC)*, New Orleans, LA, 2015, pp. 2149-2154. doi: 10.1109/WCNC.2015.7127800
- [170] R. H. Khan, S. Stüdli and J. Y. Khan, "A network controlled load management scheme for domestic charging of electric vehicles," *Australasian Universities Power Engineering Conference (AUPEC)*, Hobart, TAS, 2013, pp. 1-6, 2013.
- [171] M. Kintner-Meyer, K. P. Schneider, and R. G. Pratt, "Impacts assessment of plug-in hybrid vehicles on electric utilities and regionalUS power grid Part 1: Technical analysis Pacific Northwest National Laboratory," *Pacific Northwest Natl. Lab.*, Richland,WA, Tech. Rep. PNNL-SA-61669, 2007.
- [172] E. Sortomme and M. A. El-Sharkawi, "Optimal scheduling of vehicle to grid energy and ancillary services," *IEEE Transaction on SG*, vol. 3, no. 1, pp. 351-359, Mar. 2012
- [173] Andreas Meier, Matthias Woehrle, Mischa Weise, Jan Beutel, and Lothar Thiele, "NoSE: Efficient Maintenance and Initialization of Wireless Sensor Networks," *6th Annual IEEE Communications Society Conference on Sensor, Mesh and Ad Hoc Communications and Networks (SECON)*, pages 395-403, Rome, Italy, Piscataway, NJ, USA, 2009.
- [174] Z. Lu and H. Yang, *Unlocking the power of OPNET modeler*: Cambridge University Press, 2012
- [175] OMNet++ user manual, <https://omnetpp.org/doc/omnetpp/UserGuide.pdf>, [accessed on 15th May 2016]
- [176] www.ti.com/lit/ds/symlink/cc2530.pdf.
- [177] M. Garg, "Linear Prediction Algorithms," *Indian Institute of Technology Bombay*, April 2003.
- [178] A. O. Cinneide, "Linear prediction," *Dublin institute of technology*. Rep., 2008.
- [179] M. Takagi, Y. Iwafune, K. Yamaji, H. Yamamoto, K. Okano, R. Hiwatari, and T. Ikeya, "Electricity pricing for plug-in hybrid electric vehicles bottom charge in daily load curve based on variation method," *Proc. Rec. IEEE Power Energy Syst. Innovative SG Tech. Conf.*, Jan. 2012.
- [180] M. Kintner-Meyer, K. P. Schneider, and R. G. Pratt, "Impacts assessment of plug-in hybrid vehicles on electric utilities and regionalUS power grid Part 1: Technical analysis Pacific Northwest National Laboratory," *Pacific Northwest Natl. Lab.*, Richland,WA, Tech. Rep. PNNL-SA-61669, 2007.
- [181] E. Sortomme and M. A. El-Sharkawi, "Optimal scheduling of vehicle to grid energy and ancillary services," *IEEE Transaction on SG*, vol. 3, no. 1, pp. 351-359, Mar. 2012
- [182] E. Sortomme, M.A. El-Sharkawi, "Optimal Charging Strategies for Unidirectional Vehicle-to-Grid," *IEEE Transaction on SG*, vol.2, no.1, pp.131,138, March 2011.

- [183] AT. Al-Awami, E. Sortomme, "Coordinating Vehicle-to-Grid Services With Energy Trading," *IEEE Transaction on SG*, vol.3, no.1, pp.453,462, March 2012.
- [184] "Grid energy storage", *U.S. Department of Energy (DOE)*, December 2013.
- [185] J.W. Demmel, "Applied Numerical Linear Algebra," *Philadelphia: SIAM*, 1997.
- [186] C. Forbes, M. Evans, N. Hastings and B. Peacock, "Pareto Distribution in Statistical Distributions," Fourth Edition, John Wiley & Sons, Inc., Hoboken, NJ, USA, 2010.
- [187] <http://www.aemo.com.au/Electricity/Data/Forecast-Supply-and-Demand>
- [188] I. Papapanagiotou, D. Toumpakaris, L. Jungwon, M. Devetsikiotis, "A survey on next generation mobile WiMAX networks: objectives, features and technical challenges," *IEEE Communications Surveys & Tutorials*, vol.11, no.4, pp.3,18, Fourth Quarter 2009
- [189] F. Aalamifar, L. Lampe, S. Bavarian, E. Crozier, E, "WiMAX technology in smart distribution networks: Architecture, modeling, and applications," *IEEE PES T&D Conference and Exposition*, vol., no., pp.1,5, 14-17 April 2014.
- [190] IEEE 802.16p Task Group, "Machine-to-Machine (M2M) communication study report," May, 2010
- [191] P.P.S. Priya, V. Saminadan, "Performance analysis of WiMAX based SG communication traffic priority model," *International Conference on Communications and Signal Processing (ICCSP)*, vol., no., pp.778,782, 3-5 April 2014.
- [192] IEEE Standard for Local and metropolitan area networks "Air Interface for Fixed and Mobile Broadband Wireless Access Systems," IEEE P802.16-2009, May, 2009.
- [193] D. E. Barber, J.C. McEachen, "Geolocation of WiMAX subscriber stations based on the timing adjust ranging parameter," *4th International Conference on Signal Processing and Communication Systems (ICSPCS)*, vol., no., pp.1,5,13-15 Dec. 2010.
- [194] H.A. Mahmoud, H. Arslan, M.K. Ozdemir, "Initial Ranging for WiMAX (802.16e) OFDMA," *Military Communications Conference (MILCOM)*, vol., no., pp.1,7, 23-25 Oct. 2006.
- [195] Y. Liang; B. Chang; S. Hsieh; D. Wang, "Analytical Model of QoS-Based Fast Seamless Handoff in IEEE 802.16j WiMAX Networks," *IEEE Transactions on Vehicular Technology*, vol.59, no.7, pp.3549,3561, Sept. 2010.
- [196] D. Staehle et al, "Performance evaluation and parameterization of the IEEE 802.16 contention-based CDMA bandwidth request mechanism for the OFDMA physical layer", *portal.acm.org*, 2009.
- [197] IEEE Standard for Information technology - Telecommunications and information exchange between systems - Local and metropolitan area networks "Specific requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications", IEEE P802.11e-2005.
- [198] R. H. Khan, K. Mahata, J. Brown, "An adaptive RRM scheme for SG M2M applications over a WiMAX network," *9th International Symposium on Communication Systems, Networks & Digital Signal Processing (CSNDSP)*, vol., no., pp.820,825, 23-25 July 2014.
- [199] J. Vardakas, N. Zorba, C.V. Verikoukis, "A Survey on Demand Response Programs in SGs: Pricing Methods and Optimization Algorithms," *IEEE Communications Surveys and Tutorials*, vol.17, no.1, pp.152-178, Firstquarter 2015, doi: 10.1109/COMST.2014.2341586.
- [200] R.W. Uluski, "The role of Advanced Distribution Automation in the SG," *Power and Energy Society General Meeting*, 2010 IEEE, vol., no., pp.1-5, 25-29 July 2010 doi: 10.1109/PES.2010.5590075.
- [201] *Machine-to-Machine (M2M) communications study report*, IEEE 802.16 Broadband Wireless Access Working Group, Tech. Rep., 2010.
- [202] "Guidelines for assessing wireless standards for SG applications," *NIST Priority Action Plan 2 (PAP2)*, Tech. Rep., 2010.
- [203] K. Ahmed and M. Gregory, "Distributed Efficient Similarity Search Mechanism in Wireless Sensor Networks," *Sensors*, vol. 15, no. 3, pp. 5474-5503, May 2015.
- [204] "Power Delivery Systems," in *Power Distribution Planning Reference Book, Second Edition*, ed: CRC Press, 2004.
- [205] K. Mahmood, A. Chilwan, O. Osterbo and M. Jarschel, "On the Modeling of OpenFlow-based SDNs: The Single Node Case," *Proceedings of Computer Science and Information Technology (CS and IT)*, Vol.4, pp 207-214, 2014, doi 10.5121/csit.2014.41120.
- [206] Holmberg, Kenneth, Adgar, Adam., Arnaiz, Aitor., Jantunen, Erkki., Mascolo, Julien., & Mekid, Samir, "E-maintenance," *Dordrecht: Springer*, 2010.
- [207] K. Ahmed and M. A. Gregory, "Optimized TDMA based distance routing for Data Centric Storage," *IEEE 3rd International Conference on Networked Embedded Systems for Every Application (NESEA)*, Liverpool, 2012, pp. 1-7. doi: 10.1109/NESEA.2012.6474019
- [208] R. Jain, D. Chiu, and W. Hawe, "A Quantitative Measure of Fairness and Discrimination for Resource Allocation in Shared Computer Systems," *DEC Research Report TR-301*, September 1984.

APPENDIX A

Proof of Lemma 5.1

Proof: Let's assume the total number hop counts in a virtual grid is H , where the hop counts of switches Sw1, Sw2, Sw3, ..., Sw n to reach the controllers are denoted with $h_1, h_2, h_3, \dots, h_n$

Hence,

$$H = (h_1 + h_2 + h_3 + \dots + h_{\sqrt{\eta}}) + (h_{\sqrt{\eta}+1} + h_{\sqrt{\eta}+2} + h_{\sqrt{\eta}+3} + \dots + h_{2\sqrt{\eta}}) + (h_{2\sqrt{\eta}+1} + h_{2\sqrt{\eta}+2} + h_{2\sqrt{\eta}+3} + \dots + h_{3\sqrt{\eta}}) + \dots + (h_{(\sqrt{\eta}-1)(\sqrt{\eta}+1)} + h_{(\sqrt{\eta}-1)(\sqrt{\eta}+2)} + h_{(\sqrt{\eta}-1)(\sqrt{\eta}+3)} + \dots + h_{\eta}) \quad (1.a)$$

Then,

$$\begin{aligned} H = & \left\{ (\sqrt{\eta} - 1) + (\sqrt{\eta} - 2) + \dots + \sqrt{\eta} - \left(\frac{(\sqrt{\eta}+1)}{2} \right) + \dots + (\sqrt{\eta} - 2) + (\sqrt{\eta} - 1) \right\} + \\ & \left\{ (\sqrt{\eta} - 2) + (\sqrt{\eta} - 3) + \dots + \sqrt{\eta} - \left(\frac{(\sqrt{\eta}+1)}{2} \right) - 1 + \dots + (\sqrt{\eta} - 3) + (\sqrt{\eta} - 2) \right\} + \\ & \left\{ (\sqrt{\eta} - 3) + (\sqrt{\eta} - 4) + \dots + \sqrt{\eta} - \left(\frac{(\sqrt{\eta}+1)}{2} \right) - 2 + \dots + (\sqrt{\eta} - 4) + (\sqrt{\eta} - 3) \right\} + \dots + \\ & \left\{ (\sqrt{\eta} - 1) + (\sqrt{\eta} - 2) + \dots + \sqrt{\eta} - \left(\frac{(\sqrt{\eta}+1)}{2} \right) + \dots + (\sqrt{\eta} - 2) + (\sqrt{\eta} - 1) \right\} \end{aligned} \quad (2.a)$$

$$H = \left\{ \eta - \frac{(\sqrt{\eta}+1)^2}{4} \right\} + \left\{ \eta - \frac{(\sqrt{\eta}+1)^2}{4} - \sqrt{\eta} \right\} + \left\{ \eta - \frac{(\sqrt{\eta}+1)^2}{4} - 2\sqrt{\eta} \right\} + \dots + \left\{ \eta - \frac{(\sqrt{\eta}+1)^2}{4} \right\} \quad (3.a)$$

Thus, the average number of hops from a switch to controller would be

$$h = H/\eta \cong \sqrt{\eta}/2 \quad (4.a)$$

APPENDIX B

Linear Prediction Model

If the real-time demand information is $\{\Delta_j^k\}_{k=t-N+1}^t$, at t

Then, at time $(t+1)$, the approximate value of P_j^{t+1} will be

$$P_{t+1} = w_1 \Delta_j^{t-N+1} + w_2 \Delta_j^{t-N+2} + \dots + w_N \Delta_j^t \quad (1.b)$$

Where, P_{t+1} is the predicted value of Δ_j^{t+1} and N is the number of weighting coefficients (i.e. $w_1, w_2, w_3, \dots, w_N$). Similarly, the value of D_j^{t+2} is predicted by

$$P_{t+2} = w_1 \Delta_j^{t-N+2} + w_2 \Delta_j^{t-N+3} + \dots + w_N P_{t+1} \quad (2.b)$$

Thus, the predicted demand at time $(t+T)$ can be derived by

$$P_{t+T} = \sum_{k=1}^{T-1} P_{t+T-k} w_{N-T+2} + \sum_{k=T}^{N-T+1} \Delta_j^{t+T-k} w_{N-k} \quad (3.b)$$

Now, if M previous data samples are used (i.e. $\Delta_j^t, \Delta_j^{t-1}, \dots, \Delta_j^{t-M+1}$) to determine the coefficient 'w', where $(M > N)$

Then,

$$\Delta_m = \frac{1}{M} \sum_{k=t-M+1}^t \Delta_j^k \quad (4.b)$$

And,

$$\bar{\Delta}_j^i = \Delta_j^i - \Delta_m \quad (5.b)$$

With a simple extension of the LP algorithm we can determine W using the data samples. Let,

$$A \cdot W = Y \quad (6.b)$$

Where,

$$\begin{bmatrix} \bar{\Delta}_j^{t-M+1} & \bar{\Delta}_j^{t-M+2} & \dots & \bar{\Delta}_j^{t-M+N} \\ \bar{\Delta}_j^{t-M+2} & \bar{\Delta}_j^{t-M+3} & \dots & \bar{\Delta}_j^{t-M+N+1} \\ \vdots & \ddots & \dots & \vdots \\ \bar{\Delta}_j^{t-M+N} & \dots & \dots & \bar{\Delta}_j^{t-M+2N-1} \\ \bar{\Delta}_j^{t-M+S} & \dots & \dots & \bar{\Delta}_j^{t-1} \end{bmatrix} \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_N \end{bmatrix} = \begin{bmatrix} \bar{\Delta}_j^{t-M+N+1} \\ \bar{\Delta}_j^{t-M+N+2} \\ \vdots \\ \bar{\Delta}_j^{t-M+2N} \\ \bar{\Delta}_j^t \end{bmatrix} \quad (10)(7.b)$$

Which becomes,

$$A = \begin{bmatrix} \bar{\Delta}_j^{t-M+1} & \bar{\Delta}_j^{t-M+2} & \dots & \bar{\Delta}_j^{t-M+N} \\ \bar{\Delta}_j^{t-M+2} & \bar{\Delta}_j^{t-M+3} & \dots & \bar{\Delta}_j^{t-M+N+1} \\ \vdots & \ddots & \dots & \vdots \\ \bar{\Delta}_j^{t-M+N} & \dots & \dots & \bar{\Delta}_j^{t-M+2N-1} \\ \bar{\Delta}_j^{t-M+S} & \dots & \dots & \bar{\Delta}_j^{t-1} \end{bmatrix} \quad (8.b)$$

$$\mathbf{W} = [w_1 \ w_2 \ \dots \ w_N]^T \quad (9.b)$$

And

$$\mathbf{Y} = [\bar{\Delta}_j^{t-M+N+1}, \bar{\Delta}_j^{t-M+N+2}, \dots, \bar{\Delta}_j^{t-M+2N}, \bar{\Delta}_j^t]^T \quad (10.b)$$

Let us define,

$$\begin{cases} e_1 = |w_1 \bar{\Delta}_j^{t-M+1} + w_2 \bar{\Delta}_j^{t-M+2} + \dots + w_N \bar{\Delta}_j^{t-M+N} - \bar{\Delta}_j^{t-M+N+1}| \\ e_2 = |w_1 \bar{\Delta}_j^{t-M+2} + w_2 \bar{\Delta}_j^{t-M+3} + \dots + w_N \bar{\Delta}_j^{t-M+N+1} - \bar{\Delta}_j^{t-M+N+2}| \\ e_s = |w_1 \bar{\Delta}_j^{t-M+N} + w_2 \bar{\Delta}_j^{t-M+N+1} + \dots + w_N \bar{\Delta}_j^{t-M+2N-1} - \bar{\Delta}_j^{t-M+2N}| \end{cases} \quad (11.b)$$

Where, $|\cdot|$ indicates the absolute value. Select $w_1 \dots w_N$ to minimize $e_1, e_2 \dots e_s$ using the least square solution of (7.b) The least square solution selects w_1, w_2, \dots, w_N such that $e_1 + e_2 + \dots + e_s$ is minimized. In a mathematical form the optimization of the least square problem can be defined as

$$\min_w \|\mathbf{A} \cdot \mathbf{W} - \mathbf{Y}\|_2^2 \quad (12.b)$$

This is a convex optimization problem which can be solved by a linear programming method. In fact, the optimization has a compact form and the well-known solution of this problem is [214] which is given by

$$\mathbf{w} = (\mathbf{A}^T \mathbf{A})^{-1} \mathbf{A}^T \mathbf{Y} \quad (13.b)$$

So, (3.b) and (4.b) become

$$\bar{P}_{t+T} = \sum_{k=1}^{T-1} \bar{P}_{t+T-k} w_{N-T+2} + \sum_{k=T}^{N-T+1} \bar{\Delta}_j^{t+T-k} w_{N-K} \quad (14.b)$$

And,

$$P_{t+T} = \bar{P}_{t+T} + \Delta_m \quad (15.b)$$